PRACTICAL ENERGY AUDIT MANUAL

Industrial Electricity Supply Systems

Prepared by

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for

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PREFACE

Energy inputs - both electrical and fuel - are an essential part of manufacturing process, and expenditure on these inputs often accounts for a significant share of the manufacturing cost. This is compounded by the fact that the cost of energy is constantly escalating and will continue to rise.

Any saving in energy costs directly adds to the operating profits of the company. It probably requires less effort to improve profits through energy savings than by - reducing labour cost, increasing sales, increasing prices, reducing distribution costs, etc.

The main purpose of an energy audit is to systematically identify practical and feasible opportunities for saving all forms of energy in a plant and realise the benefit of cost reduction. Experience shows that as much as 10-15 percent of energy could be saved without any need of large investments, through energy audits.

The main objective of this manual is to familiarise the plant personnel in the techniques, methodology and approach to in-house energy audits. Since energy conservation is essentially a continuous exercise, it is inevitable that the plant personnel are able to regularly monitor trends in energy consumption and initiate remedial measures to improve energy efficiency.

Section 1: Introduction

Energy management is the philosophy of more efficient energy use, without compromising upon production levels, product quality, safety and environmental standards. However, as in any other commercial and economic facet, the concept of energy management is dominated by the cost efficacy - any project must be viable in financial terms before it can be transformed from paper to structure. Therefore, financial and technical evaluations are perceived to be essential, though necessitated to be secondary to the human resource aspect. It is inevitable that any such implementation has to overcome the Herculean hurdle of the ever-present attitude of "*no-change*" which, very often, needs a nudge to the "*change*" mode.

The energy management programme can be made "*self-financing*" - with the savings of the low-cost short term measures being utilised for the implementation of more capital-intensive measures.

Underlying the concept is a logical and comprehensive management approach. Experience shows that energy savings are significant and long lasting, when they are achieved as part of a comprehensive energy management programme. A systematic and structured approach is required to identify and realise the full potential of savings that can be achieved, mainly through low-cost measures. The basis of such a programme has to be a comprehensive and professional energy audit, in order to assess the current consumption pattern and identify potential opportunities to conserve energy, given the existing framework and infrastructure of the industry.

Energy consumption indices are indicators of the socio-economic growth of a country. Over the years, the use of energy has increased sharply in the domestic, industrial, transportation and agricultural sectors. Energy scenario is given in Table 1.1. Electrical energy, especially, is one of the most expensive forms of purchased energy, and hence, its use must be confined to optimum levels for efficient and cost effective operation.

Large industrial sectors in India, such as cement, fertilisers, petrochemicals, steel, aluminium, paper, textiles and engineering industries constantly face acute shortage of power due to the ever-increasing demand, despite increase in generation.

The current cost of power in India is Rs. 4/- per kWh on an average, and will shortly reach Rs.5/- per kWh. With the increased scarcity of large capital inflow for power generation, the popular notion of "one unit saved is two units generated" is more profound.

Hence, saving of electricity must become a way of life in every sector, not only to be cost effective globally but also to reduce the gap of demand and supply.

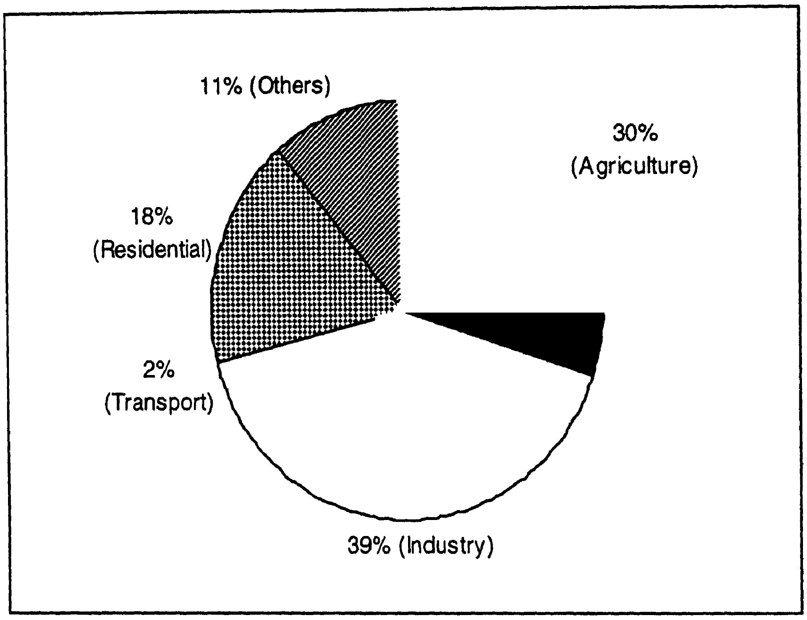


Figure 1.1 : Major Consumers of Electricity

Fig 1.1 depicts the industrial share of energy consumption vis-à-vis other sectors. (Source:TEDDY-1998/99)

Electrical energy management has to aim at proper identification, quantification and control of loads through correct application of efficiency-improvement equipment. Increasing efficiency implies reducing the energy consumption for the same output or increasing the productivity for same level of consumption of energy. The energy consumption per unit of production is treated as an index of energy efficiency.

To improve the efficiency of electricity usage, it is essential to analyse the specific end-use and derive how the overall system efficiency from supply point to consumer point can be improved. This manual aims to emphasise the means of energy efficient and supply system for the industrial sector.

Energy and Environment

The process of energy generation, transport and utilisation leads to significant environmental pollution. In the past decade, concern for the environmental pollution has increased considerably. The greenhouse effect due to increase in the level of CO_2, methane and other gases are leading to global warming. CO_2 level in the atmosphere has increased from 280 ppm in 1850 to about 360 ppm at present. The average temperature of the earth is likely to increase by 1.5 to 4 °C in the next 50 years, if emission of green house gases is not curbed. Global warming may lead to rise in sea levels, significant change in rainfall patterns, increase in frequency of heat waves, storms and other unforeseen consequences. The production of CFCs that affect the ozone layer has been phased out in developed countries. Both developed and developing countries have agreed to reduce carbon emissions.

The third conference of the parties to the UN framework on climate change was held in Kyoto, Japan, in December 1997. Under the protocol, Japan is to reduce its greenhouse gas emissions by 6%, USA by 7% and the European Union by 8%. The reductions are relative to the 1990 levels of each country and these are to be effective in the period 2008-2012. Thirty-eight industrialised nations are included in the protocol and different reduction targets have been set for each nation. The combined effect of these commitments will reduce greenhouse gas emissions of the industrialised nations by 5.2% below the 1990 level.

The Kyoto agreement requires very significant reduction in energy consumption in developed countries, while increasing production of goods and services; hence energy efficiency in developed countries is likely to improve by another 25% to 30% in the next decade.

The world is moving towards a sustainable energy future with emphasis on energy efficiency and use of renewable energy sources. A finite planet cannot support infinitely increasing consumption of goods and services. The motto for the next century is "REDUCE, REUSE, RECYCLE".

Table 1.1: Energy Scene in India

Sr.No	Energy Source	Units	1989-90	1991-92	1992-93	1993-94	1994-95	1995-96	1996-97	1997-98
	Coal									
1	Coal production (excl. lignite)	Million tons	200.9	229.2	238.1	246.0	253.8	270.1	285.7	296.0
2	Coal imports	Million tons	4.7	6.0	6.8	7.1	8.5	8.9	9.2	11.2
	Electricity									
3	Power installed capacity	MW	63636.0	69065.0	72330.0	76718.0	81164.0	83288.0	85742.0	89450.0
4	Electricity generation (public utilities)	Billion kWh)	245.1	286.7	301.1	323.3	351.2	379.7	394.5	420.2
5	Thermal generation	Billion kWh	178.7	208.7	224.5	247.7	262.9	307.5	325.9	346.0
6	Hydel generation	Billion kWh	62.1	72.8	69.8	70.4	82.5	72.2	68.6	74.2
7	Plant Load Factor (thermal)	%	56.5	55.3	57.1	61.0	60.0	64.0	64.4	64.7
8	T & D losses	%	22.9	22.8	21.8	21.4	21.1	22.3	-	-
	Oil									
9	Crude oil production	Million tons	34.2	30.4	27.0	27.0	32.2	34.6	32.9	33.8
10	Crude oil imports	Million tons	19.5	24.0	29.2	30.8	27.4	27.3	33.9	34.5
11	Petroleum products imports	Million tons	6.6	9.5	11.3	12.1	16.0	22.6	21.6	22.0
12	Consumption of Petro products	Million tons	54.1	59.6	61.7	63.3	68.1	75.1	80.1	84.1

(Source: CMIE, Mumbai)

Section 2: The Industrial Electricity Supply System

2.1 System Requirements for Industrial Plants

A typical electrical distribution facility in an industry will generally include the following:

- Power distribution systems for manufacturing and process equipment, including indoor sub-station, plant distribution, process control systems, building electrical service systems and protection systems
- Power outlet system for movable equipment, material-handling systems, transportation system
- Auxiliary systems like air-conditioning & refrigeration, compressed air system, lighting, fire alarms systems, communication and computer based equipment.
- Maintenance, canteen and medical facilities
- D G sets / co-generation equipment

2.2 Basic Design Considerations of an Electrical System

Any system planning should include certain basic considerations as given below that will support the overall flexible design and efficient operation of the plant:

- Safety of life and property including equipment.
- Reliability of system input supply and tolerance limit of interruptions
- Flexibility of plant distribution system
- Location of the plant sub-station and its deployment
- Data of electrical equipment, regulation and initial cost including capitalisation
- Simplicity /flexibility of operation and maintenance
- Overall cost including running cost
- Providing quality service
- Technical parameters and specifications of materials to follow standards in construction, installation, protection, operation and maintenance
- Adherence to laid down procedures with accountability

2.3 Planning Guide for Supply and Distribution System for a Plant

A broad guideline for an appropriate selection of the electrical system is presented below.

Step 1 involves collection of historical load details such as:

- load in kW and demand in kVA
- diversity factor

- load characteristics
- future expansion

This includes peak load, load fluctuations under various operating conditions, nature of load, PF and its variation, calculated daily, monthly and annual load factor, anticipated seasonal variation, effect of large motor starting.

Step 2 involves anticipation of the present demand over a period of time, peak load, maximum demand and demand, diversity and load factors.

Step 3 involves future demand forecasting and planning (plant expansion plans).

Step 4 requires determination of the voltage level required. Power is fed to a plant through a transmission and distribution (T&D) network. This can be provided using either high voltage & low current or vice versa. The selection of the voltage level is determined by current national and international standards, safety regulations and, of course, the economic considerations. Large consumers can reduce energy losses by drawing power at a high voltage level and distribute it inside their premises at required load centres using their own step-down transformers to match the voltage level to the equipment.

An industry classification, based on load and preferred incoming voltage, is given in Table 2.1.

Table 2.1: Industry Classification of Voltage Preferences

Industry	**Preferred Incoming Voltage Level**	**Voltage Class as per I.E. Rule**
100 MW and above	220 kV	Extra
Between (10 - 50 MW)	132 - 66 kV	High
Between (1 to 10 MW)	33 - 11 kV	High
Up to 50 kW	3 ϕ, 440 Volts	Medium/Low

Step 5 comprises the other points to be examined, in conjunction with the above, for suitable electrical supply systems. These are detailed below:

- Location of equipment
- Type of plant distribution system such as simple radial type or extended radial type, change-over schemes either at primary/secondary level ring main bus

- Analysis of manufacturing process for reliability, losses and costs in case of power interruptions.
- Voltage application required in the plant and voltage drops at all levels and at critical points.
- Calculation of short circuit analysis and selection of correct rating for circuit breaker with review of selection of protective devices.
- Station house-service unit requirement (parallel, standby or emergency operation).
- Preliminary layout drawing including provisions for future expansion.
- Detailed single line diagrams, covering all loads/supplies, including main and distribution transformers, switch gear, primary and secondary cabling, protection, insulation level co-ordination, motor starter panels and capacitor banks.

For any industrial plant, the following details become necessary:

- Power feeds (capacity, voltage and short circuit level).
- Characteristics of incoming supply at the point of feed and structure of distribution system.
- Transformers capacity, voltage class and impedance.
- Major loads and LV buses including provision for future expansion.
- Control, protection and grounding aspects adopted including the details of breakers, GOS, CT, PT and protection relays.

2.4 Characteristic Features of Power Supply

The efficient operation of any industrial plant depends on the reliability, adequacy and quality of electric power supply. The quality of AC power supply is adjudged by two main factors:

1. Voltage
2. Frequency

2.5 Voltage: Maintenance of constant voltage, within prescribed limits, by:

- Optimisation of .active power by proportionate increase or decrease in reactive power, drawn from or injected into the mains.
- Use of on-load tap changers for power transformers.
- Balancing of load between phases.
- Loading of transformer, cable/conductor appropriately.
- Parallel operation / disconnection of stand-by lines and transformers.
- Use of rescue generators at the factory power station.

- Use of harmonic filters and upgraded power control devices for non-linear loads.

a. Voltage Range, and Tolerance

The voltage ranges in which the AC installations can be classified (as per IS:12360 - 1988), according to their normal voltage for earthed and not effectively earthed systems, and the tolerances on declared voltages are given below in Table 2.2

Table 2.2: Voltage Ranges in AC Installations

Ranges	Line-to-Line rms. Values	Standard Nominal A.C. System Voltages	Tolerance on Declared Voltage	Voltage adopted for the system
I	50 V $\leq$ u $\leq$ 1000 V	Three phase - 415 V Single phase - 240 V	± 6 %	Distribution system
II A	1 kV < u $\leq$ 52 kV	3 3, 6.6, 11, 33 kV	+ 6 % & - 9%	Sub-transmission
II B	52 kV < u $\leq$ 300 kV	66, 132, 220 kV	± 12 5 %	Transmission
III C	U > 300 kV	400 kV	± 12.5 %	Transmission

u = Nominal voltage of the installation

The primary sub-transmission voltage is 33 kV (in a few states, it is 66 kV). The 33 kV network is extended from 220 / 132 / 33 kV substations. The secondary sub-transmission voltage is standardised at 11 kV. The low-tension voltage is either 415 V or 240 V, supplied to consumers.

b. Phase Voltage Imbalance in a Three Phase System

Most utilities adopt a three-phase, four-wire, grounded-star primary distribution system, so that single-phase distribution transformers can be connected directly to supply lines to cater to single-phase loads, such as residences and street lights. Variations in single-phase load distribution cause the currents in the three-phase system to vary, producing different voltage drops and causing the phase voltage to become unbalanced.

Phase to phase voltage imbalances by even 2.5 % of the nominal voltage can reduce motor efficiency up to 10 %. This causes excessive heating due to the high negative sequence current. Imbalance of more than 5 % should therefore not be permitted.

Perfect balance can never be maintained since loads continuously change. Blown fuses on three phase capacitor banks also unbalance the load and cause phase voltage imbalance.

Proper balancing of single-phase loads on the three phases on both branch circuits and feeders is necessary to keep the load and corresponding phase-voltage imbalance within reasonable limits.

The amount of voltage imbalance is better expressed in symmetrical components as the negative sequence component of the voltage.

$$\text{Voltage unbalance factor} = \frac{\text{Negative sequence voltage}}{\text{Positive sequence voltage}}$$

$$\text{Percent unbalance} = \frac{\text{Maximum deviation from average voltage}}{\text{Average voltage}} \times 100$$

c. Effects of Phase Voltage Imbalance

Unequal loads on individual phases, negative and zero phase sequence components cause overheating of transformers, cables, conductors and motors thus increasing the losses and motor malfunction. The limit of negative phase sequence as per 1EC34-1 is 2% of the voltage.

When unbalanced phase voltages are applied to three phase motors, additional negative sequence currents circulate in the motor, increasing heat losses in the rotor. The most severe condition occurs when one phase is open and the motor runs on single-phase power.

In general, single-phase loads should not be connected to three phase circuits supplying equipment sensitive to phase-voltage imbalance. A separate circuit should be used to supply such equipment.

d. Standard Voltages and Preferred H P for Induction Motors

The most important aspect of induction motors is the starting voltage, which can be best depicted as in Table 2.3.

Table 2.3: Standard Voltages and HP of Induction Motors

Standard Voltage	Preferred H. P. of Motor
440 V	Up to 1000
3.3 kV	400 to 6000
6.6 kV	400 and above
11 kV	1500 and above

e. **Voltage Drop Calculations**

i. The formula for voltage drop is expressed as

$$V = IR \, Cos\, \phi + IX \, Sin\, \phi$$

Where, V is voltage drop in one phase,
$Cos\,\phi$ = load p.f ;
$Sin\,\phi$ = Load reactive factor

For voltage drop between Line to Line, the expression is V_{line}=2 x V, whereas, for three phase system it is V_{line} = 1.73 V.

ii. The voltage drop in cable can be calculated based on manufacturer's data sheet with regard to resistance per km of cable size and, temperature.

iii. Transformer voltage drop is dependent on voltage rating and operating power factor.

iv. Motor starting voltage drop : Starting of motor draws excessive current from the system, thus causing voltage drops, unless taken care. System design should therefore include suitable motor starters as well as the cable sizes.

Selection of suitable voltage helps in reducing line losses (distribution losses). The following example depicts the line lose reduction:

A cable which is laid in a factory has to transmit a power of 150 kVA. The length is 400 m and the cross section is 70 mm^2. With the specific resistance for copper at 20 °C the power losses would be :

ρ_{20} = 0,0178. 10^{-6} Ωm, L = 400 m and A = 70 mm^2 it follows :

$$R = \frac{\rho_{20}\, L}{A} = 0.102\ \Omega$$

Power at 0.4 kV line voltage = VI^2R

$$\text{Line loss} = \frac{(150\ \text{kVA})^2}{(0.4\ \text{kV})^2} \times 0.102\ \Omega = 14344\ \text{W}$$

If 11 kV voltage is extended for the above distance

$$\text{Line loss} = \frac{(150\ \text{kVA})^2}{(10\ \text{kV})^2} \times 0.102\ \Omega = 23\ \text{W}$$

It can be observed that the power losses are reduced by 1/700 at medium voltage compared with low voltage level. The choice of voltage level depends on the location of the transformers. When planning an electrical distribution, network, it is necessary to investigate whether it is economical to install more than one transformer near the centre of electricity consumption, or to build just one central transformer station. This also involves laying of proper voltage grade cable.

2.6 Frequency

Normal frequency is ensured by supplying utility grid and depends mainly on the relation between the actual power of the supply source and the power consumed by the factory. For frequency stabilisation, it is necessary that at any time :

$$P_{actual} \geq P_{consumed}$$

Where,

P_{actual} is the actual power from the supply source
$P_{consumed}$ is the power consumed by the factory

In most power systems, a stable frequency is maintained during power shortage by automatic frequency control devices, which disconnect some of the less essential consumers. Parallel operation of the factory power station with the power grid also serves the same purpose.

2.7 Voltage and Frequency Regulation

Some permissible regulations at 60°C, according to IE Rule No. 54, include:

(i) 33 and 11 kV + 6% and -9%
(ii) Low and medium voltage ± 6%
(iii) Frequency variation permissible is ± 4%.

$$\text{Percentage regulation} = \left(\frac{V_S - V_R}{V_R}\right) \times 100$$

$$= \left(\frac{IR\cos\phi + IX\sin\phi}{V_R}\right) \times 100$$

The voltage drop under various operating conditions must be checked. In case the fluctuation in voltage is more than the operating limits, the effect on the process needs to be verified. For induction motors, if the voltage is below nameplate rating, it can cause reduced starting torque, resulting in a rise in temperature. If the voltage is higher than rated, increased torque and starting current result in a lower power factor.

In case of fluorescent lamps, the output for magnetic ballast varies directly as the applied voltage. In typical reactor ballast of mercury lamps, for a 5 % change in terminal voltage, there will be a 12 % change in the light output. Reactive output reduces by 19% for a 10% voltage drop in capacitors.

For better voltage regulation, the distribution systems should be in the following order of merit.

a) Grid network
b) Spot network
c) Primary loop
d) Radial

2.8 Harmonic Effects in the Circuit

With an increased use of non-linear devices, harmonic distortion of the voltage waveform is a problem, which is receiving considerable attention.

Harmonic currents are generated with the use of devices such as:

i) Rectifiers
ii) Inverters
iii) Thyristor-controlled VSD
iv) Induction furnaces
v) Arc furnaces
vi) Fluorescent lamps
vii) Saturable reactors

2.9 Effect of Harmonics

Harmonic distortion disrupts plants. The greatest importance is the loss of productivity. These occur because of process shutdowns due to the unexpected failure of motors, drives, power supplies or just the spurious tripping of breakers as depicted in Table 2.4. In addition, maintenance and repair budgets can be severely stretched.

Table 2.4: Consequences of harmonic distortion

Equipment	**Consequences**
Capacitors	Blown fuses, reduced capacitor life
Motors	Inability to fully load, mechanical fatigue And reduced motor life
Fuses/Breakers	False/Spurious operation and Damaged Components
Transformers	Increased copper and iron losses, Reduced capacity, increased noise and Possible insulation failure
Utility meters	Measurement errors/higher billings
Telephones	Interference (low frequency hum, noise)
Drives/Power Supplies	Miss-operation due to multiple Zero Crossing
Cable	Increased copper loss

Section 3: Electrical Energy Management In Industries

3.1 Introduction

There is a saying in energy management - "what is not measured cannot be managed". Measurement and data management are now key issues in energy management. The tools for the job are now available to manage energy in an efficient and cost effect way.

Electrical energy management of any industrial establishment is purely based on the load estimates and planning of the distribution system. Energy management is the stepping-stone for the energy conservation and cost reduction process.

Based on the load characteristics, values of connected load and load factor, the maximum demand required for a typical industry can be worked out. With the given load data and the load characteristics demand factor, diversity factor and utilisation factor can also be evaluated. Load analysis of the plant can be carried out using above mentioned factors.

Energy management can be effectively accomplished through:

a. Operation management.
b. Load management.

3.2 Operational Management

Energy accounting, monitoring and control is the very first step to be observed in any of the energy conservation management. It is of great consequence to make any program of energy management to be successful.

a) Energy Accounting

Metering of the energy consumed by an industrial establishment is necessary so that:

- Energy consumed by equipment can be analysed in detail and corrective methods can be opted for improving equipment performances
- The consumption of active energy in the individual major equipment, shops, sections, and plant can be monitored and variation in energy consumption in relation to production levels can be analysed.
- The above analysis helps in bench-marking to arrive at optimum

specific energy consumption and reduce process irregularities

- The production of reactive energy by the compensating units of the factory may be monitored and corrective steps can be adopted
- It helps in identifying the optimum usage of demand allocation, thereby improving the load factor
- Any consumers supplied via the factory substation may be charged.
- Energy accounting for the corresponding sections (i.e. individual profit centre concept) can be initiated towards input cost analysis.
- Energy accounting shall help in correlating the daily, fortnightly, monthly, or annual energy consumption index with indication of deviation from the benchmark or the set target.

b) Monitoring and Control

It is always the best practice to install energy meters, hour meters (time totalisers) on major equipment/systems (HVAC system, Compressed air system, Pumping system, etc.,) consuming significant amount of energy. This shall help in accounting energy consumption on a shift-wise basis, daily basis, month-wise and yearly basis. Co-relation of these consumption patterns with the production details (shift-wise production, equipment-wise production) shall lead to identify energy saving opportunities.

The summation of all sub-meter energy consumption should be compared with the summation of main plant energy meter (check meter for grid energy meter) and the energy meters of the DG sets. Energy accounting error of about 5% between the summed values of sub-metering, main plant check meter and DG set energy meter to that of grid energy meters is reasonable. Enormous percentage error in the readings recorded needs to be viewed seriously.

c) House keeping measures

House keeping and periodic maintenance of equipment play an important role in getting desired performance and efficiency. Preventive maintenance schedules for all equipment/system should be adhered to. These measures can be easily implemented to achieve energy savings even to the tune of 10%, with little or no investment. Few such examples are:

- Stopping idle running of electrical machinery
- Turning off lights and ventilation fan when not required

- Cleaning or changing air filters (e.g. AHU, compressor suction filters)
- Cleaning heat exchangers (scaling/fouling)
- Avoiding empty idle run of conveyers during break period
- Shutting down redundant motors, pumps, and fans.
- Improving insulation (e.g. steam pipes, refrigerant pipes, ducts etc.,)
- Rectifying faulty control instruments and regulating the correct control settings (e.g. thermostat settings in room air conditioners).
- Interlocking arrangement between various equipment/subsystem for an efficient integrated operation (e.g. interlock mechanism for chiller pump and chiller compressor, cooling tower fan and cooling water pump, exhaust blower and conveyor belt for heat treatment system etc.)

d) Reduction of Losses

It must be noted that, due to the excellent quality of insulating material, loss of electricity due to leakage is negligible. The only significant losses in electrical equipment are cable losses, distribution transformer losses and losses in motors, and indirect effect of leakage of water, compressed air or chilled water from pipe lines. Radiation loss from heated surfaces is another important loss factor. In many furnaces, the overall efficiency may be 50% to 60%. Waste heat recovery is another important factor, which needs careful consideration.

e) End-use minimisation

For each energy intensive end-use such as compressed air, chilled water, heating and melting, the plant operation must be evaluated to moderate the quantity and quality. Some examples are reducing the temperature for heat treatment, lowering compressed air pressure, increasing chilled water temperature or reducing flow in heat exchangers. A few typical instances are given below:

1. Use of compressed air for cleaning substantially reduced in process and engineering industries.
2. For applications with chilled water temperature of 10 - 15^{0}C, cooling tower water has been used, especially in winter season.
3. Instead of uniform lighting in offices and factories, task lighting has been provided, so that light is available when and where it is required.
4. Vacuum in paper machines is maintained at optimum level, determined by paper quality.

5. Relative humidity levels reduced in textile mills. In a recent development, relative humidity at 80% RH is maintained near the looms only, rather than in the whole loom shed.
6. Air conditioning replaced by air-cooling in many plants, leading to a saving of 75% to 80%.

f) Equipment Operation at Optimum Capacity

Equipment like motors, pumps, fans, compressors, furnaces and machine tools are designed for certain rated capacity. The performance and efficiency of these equipment is highest at a point close to the rated capacity. Deviation from this capacity can significantly affect performance.

For an energy efficient motor, whose efficiency is higher above 60% load, the efficiency drops considerably, if the motor is loaded only 40% and below. Similarly, screw compressors have low part-load efficiency. For electrolytic cell lines, operation at lower current density leads to better efficiency, although production also decreases.

Pumps and fans would give guaranteed efficiency only at design head and flow.

Pump operation at reduced flow (30% different from that of designed flow) leads to poor efficiency. Thus, operation of one pump at rated capacity can lead to a significant saving, compared to two pumps at half load.

Similarly, pipelines for compressed air, water and other fluids have certain design capacities. Operation beyond capacities can lead to significant losses. However, for pipelines, working at less than design flow, friction losses reduce drastically.

Examples:

1. Oversized motors are replaced by properly sized motors in number of industries.
2. Oversized pumps are replaced by smaller pumps (or impellers trimmed to operate at required field conditions). Change in speed also can bring operation near optimum efficiency.
3. In number of vanaspati plants, operation at reduced current density for electrolysis of water led to 10% to 15% savings.
4. In engineering industries, sizes of ovens and furnaces reduced to

match with load, leading to energy savings of 30% to 50%.

5. In many chemical plants, inadequate pipe sizes may result in high friction losses. This in-turn forced deployment of several pumps without required increase in flow. Replacement by large size pipes have resulted in increased flow and reduced power consumption.

g) Selection of Most Efficient Equipment or Efficient Process for operation

The efficiency of similar equipment can be different due to design, ageing, maintenance and other factors. Some idea of the relative efficiency of different lines of equipment is necessary to maximise the use of efficient equipment.

Example:

1. In an engineering industry, difference in power consumption between two air compressors of similar capacity was found to be 20%.
2. In melting and heat-treatment furnaces, a difference in efficiencies of 10% to 20% has been commonly observed.
3. In a process plant, refrigeration compressors had efficiencies ranging from 1.4 kW/ton to 0.9 kW/ton.
4. Power consumption of ring frame machine by different textile machine manufacturers is found to be different.
5. Alternative fuel usage can result in substantial cost savings.

h) Use of Technology up-grades

Increasing energy prices have led to design of equipment with higher efficiencies. More efficient boilers, motors, pumps, fans, refrigerators, lamps are all available. Many of these uses more material, heat transfer area, etc. and hence are more expensive than conventional equipment. The initial cost of equipment is negligible, compared to running costs and hence equipment selection should be based on total life cycle costs, rather than initial cost.

Examples:

1. High efficiency motors give better efficiency even at lower loads depending on type and size. Many textile mills use high efficiency motors.
2. Improved aerodynamic designs of large fans used in cement, process plants and boilers have improved efficiencies from 60% to 80% and above. Many cement plants have changed over to high efficiency

fans.

3. Many process industries have replaced inefficient aluminium or fabricated steel fans by moulded FRP fans with aerofoil designs. Savings achieved are in range of 15% to 40%.
4. Compact fluorescent lamps (9W to 18W) can replace incandescent lamps of 4 to 5 times their rating. This results in saving 75% to 80% of energy.
5. Electronic ballast consume 1 to 2 W power compared to 10 to 15 W of electromagnetic ballast.
6. Many new centrifugal chillers with better heat transfer materials and designs give 0.6 to 0.8 kW/ton compared to 1.0 kW/ton for older chillers.
7. In a pharmaceutical plant, for laboratory heating, more efficient microwave ovens are used in place of conventional steam heated ovens.

Some examples of recent technologies are given below:

- Membrane technology for caustic soda consumes 2200 kWh/ton compared to 3000 kWh/ton for older mercury cells.
- Redesigning of the distillation column for oxygen production from air consumes 1.1 kWh/Nm^3 of oxygen compared to 2.25 kWh/NM^3 in older plants. The new design allows air at 45 kg/cm^2 compared to earlier air pressure of 150 kg/cm^2.
- New process of manufacturing polyethylene using new solvents and catalysts at lower pressures uses only 25% of energy compared to older process.
- Mechanical transport of materials like wood chips, cement instead of pneumatic transport, saves 75% to 90% energy.

3.3 Load Management

Load management is a direct fall out of systematic and methodical study of electrical systems. Electrical load management is detailed in the preceding chapter (chapter-4).

3.4 Energy audit as a tool

For any energy conservation drive the essential requirement is to approach the present problem in a systematic manner. This gives not only an insight into the problem but also helps in identifying the underlying reason and the remedy there of.

Energy audit technique is such an effective tool for initiating or carrying out the process of energy management in an organisation.

a) Objectives of Energy Audit

The two basic objectives of energy audit are

1. To assist management in identifying the areas of energy waste.
2. To assist management in reducing the energy cost in the operation and there by increasing profitability of the industry.

Other indirect benefits are increasing awareness among the employees, improving working and operating methods and procedures etc.

Energy audit can be carried out in house. It can also be carried out by expert audit organisations. In case of very large industrial complexes, it is advisable to engage the services of energy manager directly reporting to CEO. Occasionally, external auditors provide checks and balances of internal audit. Small, medium and large sized industries generally find it convenient to appoint external auditors. However all audit report must be examined by the concerned management before implementation.

b) Scope of Audit

It is important to identify the type of industry in respect of generation, distribution and utilisation of electrical energy. Broadly they are categorised into three types:

1. Industry with 100% captive power generation and no grid power.
2. Industry without power generation and only grid power.
3. Industry with part power generation and grid power.

In case of industries having no power generation, power distribution and utilisation areas need to be examined and consumption of electricity in the process/production units need to be reviewed. In case of industries with power generation facilities, in addition to the above, use of electricity in generating plant also need to be examined.

Generally electrical system energy audit will cover the following areas of plant and equipment.

1. Electrical load management.
2. Transformer load management.
3. Power factor management and distribution system losses.
4. Power quality in AC system

Further the scope of energy audit encompasses any or all of the following areas:

1. Induction motors.
2. Pumps and fans.
3. Boilers
4. Furnaces and heat treatment equipment
5. Air conditioning and refrigeration/ HVAC system
6. Compressed air system.
7. Illumination system.
8. Variable speed drives.

c) Methodology of Audits

The energy auditors for the purpose of analysis adopt the following methods:

Walk Through Audit

This method is the easiest way to find out wastage and misuse of energy on day-to-day basis. Quick action can be taken to rectify the situation. It involves study of energy flow profile, energy data, process system and drawings pertaining to the layout of equipment.

A "Walk Through Audit " of the plant is then carried out to identify the energy consuming equipment.

Plant-Wise ABC Analysis

Audit can be prioritised according to quantum of consumption. High priority is given to those 'A' Category plants, which consume 70% to 80% of electrical energy in the factory. Through 'B' and 'C' Category plants could be taken up in due course, return being very attractive, in case of 'A: Category plants, priority for audit is given to the 'A' Category.

Power Demand And Consumption Norms

This is a very important aspect in assessing whether the plant is operating at optimum energy level. Such optimum energy levels can be obtained from the running plants elsewhere in the country or abroad and a comparison can be drawn.

Energy Conservation

Energy audit contributes to energy conservation (ENCON). ENCON is of prime importance in the present context of energy scenario in India since electrical energy has become scarce and demands are outstripping the supply. It is therefore a national responsibility to ensure that electrical energy is conserved to avoid wastage, no matter what concessions are given in the form of duties, taxes or in evaluating depreciation.

Analysis of Audit Results and Identification of Energy Management Opportunities

Often energy audit will identify immediate energy management opportunities, viz; unoccupied areas which have been inadvertently illumined 24 hours per day, equipment operating needlessly etc. Corrective housekeeping and maintenance action can be instituted to achieve short-term savings with little or no capital investment.

Analysis of audit data is required for a more critical investigation of the potentials for conservation. This includes a detailed energy balance of each process, activity or facility. Process modifications and alternatives to equipment design should be formulated based on technical feasibility. Economic studies to determine payback return on investment, and net savings are essential before making capital investment.

Instruments for Energy Auditing

Portable hand held power analysers, load managers, energy loggers, lux meter and other instruments are used to measure various parameters like voltage, current, frequency, power factor, active power, reactive power and apparent power. Basic Instruments required for energy auditing is listed below:

a. ***AC/DC Clamp on Portable Power meter:*** Measurement of

instantaneous values of Active power, Reactive power, Power factor, Frequency, Current & Voltage;
Range: Current – 200/1000A; Voltage – 750 V; Power – 20/200kW; Frequency – 200 Hz.

b. ***Portable Load Manager or 3-Phase Power Analyser:*** Measures and records Active Power, Apparent Power, Reactive Power, Power factor, Frequency, Current and voltage with Alarms for Peak values (user selectable); kWh, kVAh, kVArh counter; Energy Voltage & Current Harmonic Analysis upto 50^{th} harmonic; Software capable of displaying Current/Voltage waveforms.
Range: Current – 1000A; Voltage – 600 V;

c. ***Digital Lux meter or Illuminometer:*** Measurement of illumination levels;
Range: 0 – 50,000 Lux.

d. ***Digital Multimeter:*** Measurement of AC/DC Voltage; AC/DC Current; Resistance; Frequency; Continuity Test etc;
Range: DC Voltage – 0 to 1000V DC; AC Voltage – 200mV to 1000 V; AC/DC Current- 200 μA to 2000mA; Resistance- 200 ohms to 300 M ohms; Frequency- 12 Hz to 700 kHz.

The measured data helps for:

- Analysis of loading consumption pattern
- Monitor events e.g. voltage dips, swell etc., for power quality analysis
- Check correct sizing of equipment
- Solve power factor correction problems
- Identify and eliminate peaks loads and associated power problems.
- Harmonic frequency analysis

3.5 Summary

Any successful electrical energy management program for an industrial unit aims to save both energy and money associated with energy and demand savings.

As Energy Management implies providing energy service to an organisation at an optimum cost, the task invariably includes the following:

- Development of an energy information system to monitor, control and forecast consumption of various forms of energy, cost of various forms of energy, relation of energy consumption to production and optimising production cost.
- Short term and long term planning for energy needs of an industry keeping

availability and prices of different fuels in view.

- Preparation and execution of a plan for improving energy efficiency.
- Keeping track of legal, safety and environmental factors related to energy use.
- Development of human resources to take care of energy management.

Maximising efficiency implies:

- Enabling a higher standard of operation and maintenance
- Encouraging energy awareness in the workforce
- Providing capability for remote monitoring and control of these services
- Providing management with information on energy flows, consumption, trends and performances

Reducing the maximum demand and reducing losses of electrical equipment, as well as increasing the efficiency of the systems can achieve the electric energy saving opportunities, termed electrical load management.

With advances in computer technology; computerised energy management system can record and control, on a closed loop basis, various electrical parameters.

The functions that an energy management system can handle depend on the size of the system. A comprehensive system for all functions, at an effective cost, is the most desirable one. An energy audit is required to determine how and where energy is being consumed, in order to select a suitable energy management system.

3.6 Conclusion

Electrical audit is a powerful tool intended to assist management in the conservation of energy and efficient & profitable operation of industry.

Section 4: Electrical Load Management

4.1 Introduction

Electrical load management is the process of scheduling load usage so as to reduce electricity use during peak load periods. Load management generally means effectively shaving peaks and filling valleys. The goal of a load management programme is to maintain, as nearly, as possible, a constant level of load, thereby allowing the system load factor to approach 100 percent.

The major benefit from load management is a reduction in the peak demand, which would reduce the demand charges. It would also release a part of the system capacity for additional loads (in case of any expansion) to be placed on the system without the need for an additional transformer. Provided of course, that the additional load does not exceed the difference between the reduced peak load and the capacity of the existing transformer.

To conduct a load management programme it is essential that the system load curve for the plant be defined to ascertain the peak load. Peaks may occur either due to system faults or due to improper management. Monitoring and analysing the load curve on a regular basis shall ascertain the cause for peaks. On the basis of this analysis, loads can be rescheduled to reduce the peaks. This would depend on the operational constraints and whether or not the loads can be rescheduled.

4.2 Demand Management

Normally an industry is bound under a contract for power demand with State Electricity Board/utility. When power demand exceeds contract demand with state Electricity Board, industry is subjected to penalty payment imposed by the Electricity Board. This is the area where industries need to concentrate, and proper demand management systems are incorporated in the day to day functioning of the plant. It is necessary to keep and maintain adequate data and records of power imports in kVA, power factor and energy. It is useful to prepare trend charts of import power demand and also total energy imported. All abnormal peak demands must be analysed thoroughly and remedial measures are to be taken.

Demand management commonly refers to a set of measures taken to reduce the maximum demand of the system without affecting the plant output.

The conventional methods used to achieve this purpose are:

- Staggering of working of sub-plants.
- Voltage reduction (Voltage co-ordination and regulation)
- Shedding (arbitrary) of loads.
- May use alternative source of electrical energy, providing cogeneration/captive generating units.
- Storage of products like water at higher level, components for assembly, fluids at higher/lower temperature etc.,)
- By PF improvement kVA reduction is achieved.

For proper scheduling of loads one must identify loads that are:

- Non-essential.
- Controllable.
- Substantial.

Control schedule for a set of loads with known characteristics should be prepared.

- Minimum working time per cycle.
- Maximum duration of interruption.
- PLC operation of cyclic loads.
- Maximum cycling frequency based on gain of experience from operation

Plotting daily/weekly demand curves identifies peak demand and its occurrence. This would help in improving system load factor for a given time interval which is the basic aim of load management.

Load factor is defined as the ratio of the average demand to that of peak demand.

How to control the peak

Demand control, to limit peak, power, can be effected by three basic methods:

i) Timed control
ii) Manual control
iii) Centralised control

In timed control, loads are switched off or on according to a continuous cycle based on an estimate of peak load times. In this control there is no input concerning the rate of energy consumption by the load. Therefore, the

effectiveness of timed control depends on a consistent cyclic energy consumption pattern.

In the manual control method, an operator monitors a demand meter at all demand intervals that occur during peak load periods and determines when to turn off or turn on loads so as to prevent the demand from exceeding a predetermined limit. Since this method is dependent on human decision-making ability, its accuracy decreases with increasing number of loads to be controlled.

Systems having many loads are best controlled by instrumentation such as hardwired controllers and computers. Centralised control devices monitor the system energy consumption and/or the demand and decide when loads should be switched off or on. The process of switching loads off or on is referred to as load shedding or load restoring. The total possible Load Shedding Potential (LSP) for a system is given by:

$$LSP = \frac{1}{\Delta t} \sum_{i=1}^{n} (L_i \times t_{off})$$

Where, Δt is the demand interval in minutes, L_i is the load (kW) under consideration for shedding, and t_{off} is the allowable off-time in minutes during the demand interval of the L_i load. The LSP represents the maximum possible reduction in demand for the system through load shedding.

Loads that are shed are restored after permissible off time. The restored loads may, be recoverable or non-recoverable. Recoverable loads are those in which, the amount of energy saved during the shedding time of the load would be consumed after the load is restored to regain the normal operating level. For example, a pump, which has been switched off to reduce consumption during peak load periods, would consume the required amount of energy when it is switched on later during non-peak hours. In this case no energy is conserved but since the energy consumption has been deferred from a peak load period to an off-peak load period, the system load factor improves and demand charges, where applicable, are reduced. In case of non-recoverable loads not only, is the demand reduced but energy is also recovered. For example, ventilation and exhaust fans would not consume any extra energy after they are restored to regain the normal operating level.

In determining loads, which could be shed, it is important to study loads in terms of any harmful effects that could result due to load-shedding operations. For example, large motors may not be good candidates for load shedding because of

the large inrush starting currents and start/stop stresses (however, where possible, their operating time could be deferred). Production loads which can not be turned off at will are termed as base loads.

Centralised demand control for load management requires adequate instrumentation for data acquisition so that energy consumption can be monitored. Demand monitors are commercially available which can be programmed for a pre-determined demand. As soon as the load increases beyond the fixed demand, loads are shed according to a pre-programmed priority. Loads are later restored as the demand reduces. Demand monitors normally operate based on a comparison of the instantaneous rate of energy consumption to a preset ideal rate.

Advantages of centralised control for electrical demand are:

1. Accurate prediction of demand.
2. Graphical display of load and its limits.
3. Audio-visual alarm.
4. Automatic load shedding in a phased sequence.
5. Automatic restoration of load.
6. Recording and metering.
7. Adequate instrumentation for data acquisition (SCADA system).

Maximum demand Controller cuts off the peak and fills the valleys in load curve When maximum demand increases above the set value, non-critical loads are switched off. This helps in maintaining the maximum demand within sanctioned figure and in avoiding penalty.

4.3 Transformer Load Management

The operation of a transformer is based on 'Faraday's Law of Induction' By the right choice of power level and location it is possible to establish an optimal use of transformers. In contrast to the ideal transformer the real transformer has losses.

These are:

- open-circuit losses (iron losses in the core and ohmic losses of the open circuit current)
- short-circuit losses (conductor and eddy-current losses)

The open circuit losses are independent of the power, which is consumed by the transformer. These losses can be reduced by construction i.e. raising the cross-section of limb or using novel ferromagnetic material.

The short circuit losses increase with the square of power. Increasing the cross-section of the conductors of the windings can only lower them.

Most of the transformers used in electrical power systems are three-phase transformers. They can be characterised by the vector group and the type of cooling. The vector group (e.g. star connection, delta connection) depends on the internal connection of windings of the high voltage and low voltage side.

Cooling of the transformer is performed by air or a liquid, e.g. oil or askarel with a natural or forced flow. The heat is drawn off using cooling ribs at the surface of the tank.

In most cases the power losses can only be ascertained through the test certificate issued by the manufacturer or by carrying out field measurements.

a) Reduction of transformer losses

The total losses (P) of a transformer during operation are:

$$P = P_o + (P_s/P_n)^2 \times P_{sc}$$

with
- P total power losses in kW
- P_o open circuit losses in kW (no-load losses)
- P_{sc} short-circuit losses in kW (load losses)
- P_s actual load of transformer in kVA
- P_n rated power of transformer in kVA

The total losses in a transformer consist of two parts, one is constant and the second increases with the square of the load. Normally, open circuit losses (P_o) are of the order of 0.2 to 0.5% of the nominal power; whereas the short circuit losses (P_{sc}) are 0.7 to 2.1% of the nominal power. Because it is unusual to operate transformers always at full load it is sometimes more important to decrease the open-circuit losses than the short-circuit losses. When planning the installation of a new transformer in an electrical system, it is necessary to compare different designs of transformers. A special transformer with reduced open-circuit losses might be of interest. An example of transformer losses is given in figure 4.1 below.

At the time of installation of a new transformer the size is decided based on the expected loading on the transformer. Normally maximum efficiency; of the transformer is designed at the loading in the range of 50 to 65% of' its full load capacity. If the average load is 80% or more of the rated power, a bigger transformer or a second transformer should be considered because the short-circuit losses become a large portion of the total losses.

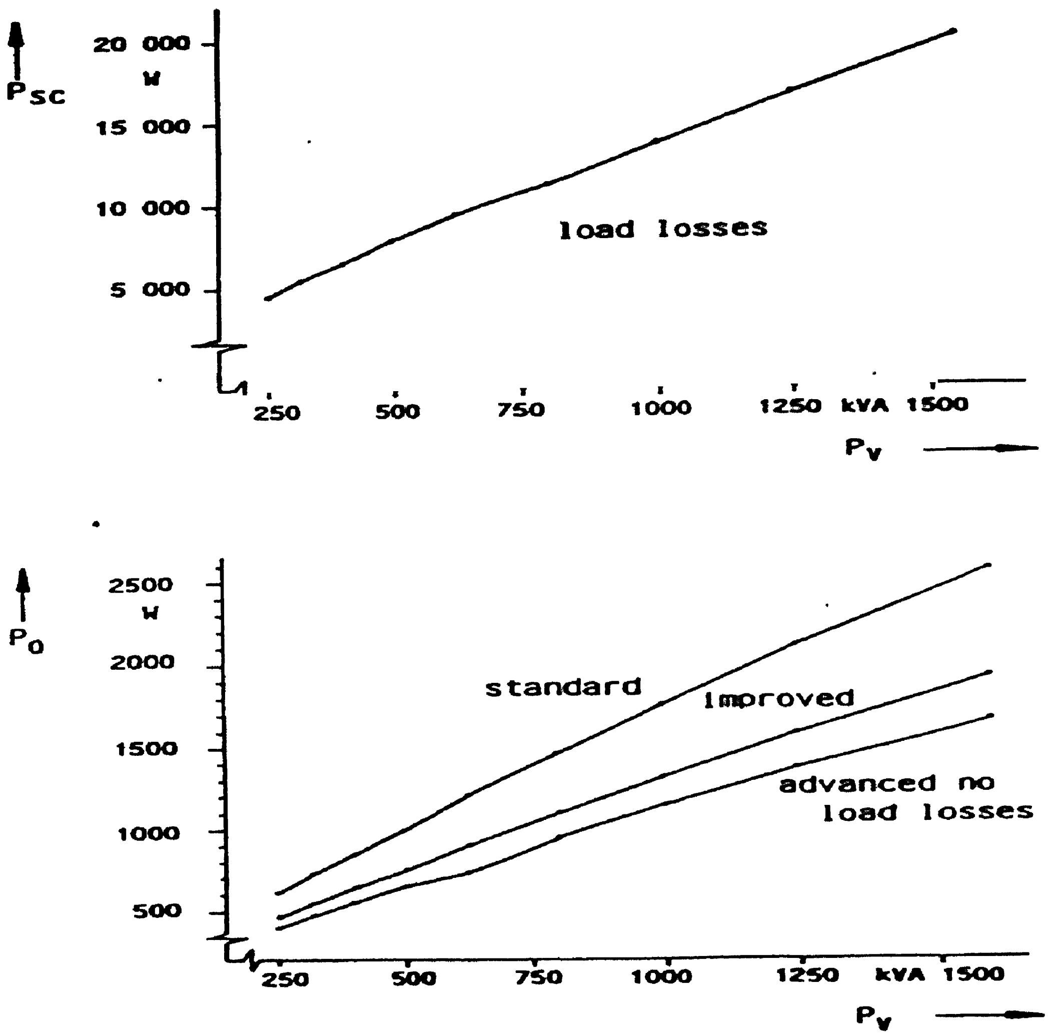


Figure 4.1: Transformer losses

b) Capacity & Number of Transformers

The main factors which should be taken into account when determining the number and capacity of shop transformers are :

a) First cost.
b) Operating cost.
c) Amount of non-ferrous metals required.
d) Reliability of supply and
e) Load to be served.

The number of transformers depends upon the operating duty of the station or industry. The load curve may show that the installation of two transformers instead of one is more attractive economically. This is usually the case when the load capacity factor is low (less than or equal to 0.5). In this case disconnecting devices are necessary to connect and disconnect the power transformers to ensure economical operation.

Where possible the installation of either one transformer or two transformers connected through a common circuit breaker should be contemplated. If the reliability of supply necessitates the installation of more than one transformer should be sought. When designing substations, redundancy features (Reserve facility) should be taken care of as follows:

Utilisation equipment of the 1st category should be supplied from two independent sources, where continuity of supply is ensured. The capacity of the transformers should be so selected that if one of the transformers fails, the remaining transformer shall ensure supply to the equipments without undue overload.

In selecting transformer capacity, it should be ensured for economical operation so that when one of the transformers is out of service, the load on the transformer in operation as far as temperature is concerned shall not affect its service life.

It is always a good practice to provide / or install transformers of one step higher in capacity. For example: If two transformers each rated for 1000 kVA are installed their foundations and structures should be so designed as to make possible the installation of two transformers of 1500 kVA each without much material modifications.

c) **Reduction in transformer losses through proper load distribution**

The objective of the transformer audit is to provide better quality of power to different load centers in the plant at high overall efficiency. In a medium and large industrial unit, there are number of transformers feeding power to the loads in the plant. These distribution transformers are sometimes not optimally loaded and there exists energy saving opportunity by shifting the load from overloaded transformer to the under-loaded one.

In a chemical unit, four 2000 kVA transformers were operating at designed maximum efficiency at 34 percent (670 kVA) of the rated load. It was observed that maximum loading on these transformers T1, T2, T3 and T4 was 64.8 percent, 31.3 percent, 53 percent and 7.4 percent respectively. i.e. only one transformer was optimally loaded, two were loaded more and one less than the required loading for maximum efficiency.

If the load on T4 is supplied from T2 and transformer T4 is de-energised, this would result in the transformer T2 to operate at a maximum load of 38.4 percent. This measure would result only in a marginal drop in maximum efficiency of T2 and average losses would increase by 1.02 kW due to increased loading. The benefit from de-energising the transformer T4 will be a saving of reduced transformer losses. The overall saving by implementing the above measure will be 13,000 kWh /year.

4.4 Power factor & Distribution Loss Management

Power factor is defined as the ratio of real power (kW) to the apparent power (kVA) and is the cosine of the angle by which the current lags (or leads) the voltage. In case of inductive loads, the current lags the voltage and the power factor is 'lagging': whereas in the case of capacitive loads the current leads the voltage and the power factor is 'leading'.

Most industrial electric loads like motors, welding sets, light sources using ballasts etc. are inductive in nature and the overall power factor of the plant is low and lagging. Poor power factor results in increased reactive current resulting, in increased total current drawn which is the vector sum of the reactive and working components of the current as given by:

$$I_t = \sqrt{(I_w)^2 + (I_m)^2}$$

Where, I_t is the total current, I_w is the working component of the total current and the I_m is the magnetizing component. With an increase in the total current drawn, the I^2R losses in the line increase, which also results in greater voltage drop across the line leading to poor voltage regulation. Poor power factor also results in increased reactive power, which leads to increased kVA demand that is given by:

$$kVA = \sqrt{(kW)^2 + (kVAr)^2}$$

Where kVA is the apparent power, kW is the real component and KVAr the reactive component of power.

a) Methods of improving power factor

Poor power factor can be corrected by either using shunt capacitors or by using synchronous motors which can be operated at leading power factor to compensate for loads with lagging power factor. Synchronous motors are very expensive and are used only in a very few industries; therefore the use of shunt capacitors is most suitable and widely acceptable for power factor improvement.

Installation of capacitors results in leading current and thus compensate for the lagging current drawn by the load. To determine the rating of a capacitor required for a particular load; it is necessary to determine the reactive power of the load.

The issues of power factor management are dealt in the Chapter. 5.

b) Distribution System Loading

Transformers and overhead lines and cables form the main power distribution system with the industry. The loading of these equipment decide the distribution system losses in the plant.

Cables that form major part of the distribution system consume reactive power. Flow of lagging reactive power leads to following causes.

- Increase in voltage regulation.
- Larger I^2R losses in system components due to high magnitudes of current for the same active power supplied.

- Requirement of larger capacity of cables for the same active power due to high current.

Distribution system losses in the industrial system range from 1-5% depending on system and extent of load employed in the plant. Normally about 2-4% losses are envisaged in cables.

The power losses vary with the square of the line currents. The peak kW losses in cables depends on the resistance of the conductor per km and the maximum load it can carry. The energy losses strongly depend on load factor and on the loss load factor.

The annual energy losses of the line can be easily calculated knowing the peak load and loss load factor for a particular cable under consideration .

$$\text{Energy loss} = \frac{3 \times I^2R}{1000} \times \text{LLF} \times 8760 \text{ kWh}$$

$$= \frac{3 \times (\text{kVA})^2 \times R}{(V_{LL})^2 \times 1000} \times \text{LLF} \times 8760 \text{ kWh}$$

Where,

I	=	Line current in amps
V_{LL}	=	Line voltage
kVA	=	Peak load
LLF	=	Loss load factor
R	=	Cable resistance in ohms /KM
8760	=	Annual operating hours

These losses can be reduced to a greater extent by way of compensation of reactive power at the receiving end of the transmission line or cable.

It is economically justified to improve the power factor for reactive compensation as the % reduction in losses is governed by the equation:

$$\%\text{ Loss Reduction} = \frac{(1- (\text{Old} \cos\phi)^2)}{(\text{New} \cos\phi)^2} \times 100$$

For a long distance cables the voltage drop is approximately governed by equation:

$$\Delta V = I\ (R \cos\phi + x \sin\phi)$$

Where,

I = Current

R & X = Resistance & reactance of the cable

ϕ = Power factor angle

$I\cos\phi$ remains constant for a given active power demand of the load while $I\sin\phi$ reduces due to reactive compensation. Thus the voltage drop at the receiving end will be very less or in other words, the voltage improvement at load side is considerable and given by equation.

$$\% \Delta V = \frac{\text{Capacitor kVAr} \times \text{`}X\text{'}}{(V_{LL})^2 \times 10}$$

Where,

V_{LL} = Voltage line to line

X = Reactance of cable in ohms

Thus, reactive power compensation would result in following benefits to the system.

a. Reduction in losses
b. Improvement in voltage profile
c. Release of system capacity

These benefits have economic impact also and usually industries employ higher cable sizes / parallel run of adequate cable sizes for future addition of capacity.

4.5 Power Quality Management

The term "power quality" has many different meanings. Electric utilities may describe power quality as reliability and quote statistics stating that the system is 99 percent reliable. The equipment manufacturer often defines power quality as the characteristics of the power supply, which may vary drastically for different vendors. However, customers are the group ultimately affected by power quality related-problems, and the best definition must include their perspective. Considering each of these factors, the following definition is often used:

"Any power problem manifested in voltage, current, or frequency deviations that results in the failure or improper operation of customer equipment."

Manufacturing and control processes in industrial facilities are increasingly dependent on equipment that is highly sensitive to power system disturbances. This has led to a greater focus on the quality and reliability of electric power. Also, the "power quality issue" is a factor associated with the increased automation of manufacturing processes and the expanded use of energy-efficient power technologies such as adjustable-speed drives.

Assessing the Problem – Harmonic Audit

Industrial power systems are highly complex, and require careful consideration of all possible problems, probable causes, and potential solutions to ensure reliable performance. TERI's experience in industrial power system studies, plus its extensive track record in helping categorize and solve power quality problems, makes us the logical choice for identifying, studying, and fixing customer power system problems.

Chapter 6 deals in detail about power quality in AC system

4.6 Summary

Broadly the Electrical load management analysis can be carried out on the following lines:

a. Develop a line diagram for the distribution system from incoming supply point up to load control centres.

b. Check existing pattern of electrical energy use and identify opportunities for possible reduction.

c. Collect annual data on :
   - Monthly bills, (Reading date, units consumed, kVA demand)
   - Reporting on kVAr, p.f., penalty for the same if any
   - Power bill as above including fuel escalation charges which is dependent on the electricity tariff
   - Other fuel bills
   - Plant operation, equipment, energy consuming areas and equipment
   - Specific energy consumption, department-wise and process-wise
   - Production level and relation to energy consumption

d. Evaluate major energy consuming equipment for:
   - Name-plate data relating to equipment
   - Efficiency tests
   - Establish current operating hours

e. Use area wise appraisal with instrument based measured parameters to identify areas for optimisation of energy use such as:
   - Demand management
   - Transformer Load Management
   - Choice of optimum operating voltage
   - Automatic control of operations
   - Power Factor Management
   - Power quality issues
   - Sizing/loading of electric motors & selecting the optimum size suiting to the application
   - Lighting reduction / changes in orientation
   - Energy efficient luminaire selection

   Quantification of energy conservation opportunities and development of a prioritised list of projects with a high rate of return can be then undertaken.

4.7 Conclusion

Electrical audit is a powerful tool intended to assist management in the conservation of energy and efficient & profitable operation of industry.

Load management would have far reaching benefits since a reduction in the peak load would be reflected not only in reduced demand charges but also in reduced line losses and consequently, improved voltage regulation and improved system efficiency.

Section 5 : Power Factor Management

5.1 The nature of reactive energy

Alternating current systems supply two forms of energy:

- "active" energy measured in kilowatt hours (kWh) which is converted into mechanical work, heat, light, etc.
- "reactive" energy, which again takes two forms:

    - "reactive" energy required by inductive circuits (transformers, motors, etc.),
    - "reactive" energy required by capacitive circuits (cable capacitance, power capacitors, etc).

All inductive (i.e. electromagnet) machines and devices that operate on a.c. systems, convert electrical energy from the power-system generators into mechanical work and heat. This energy is measured by kWh meters, and is referred to as 'active' or 'wattful' energy, In order to perform this conversion, magnetic fields have to be established in the machines, and these fields are associated with another form of energy to be supplied from the power system, known as reactive' or 'wattless' energy.

The reason for this is that inductive plant cyclically absorbs energy from the system (during the build-up of the magnetic fields) and re-injects that energy into the system (during the collapse of the magnetic fields) twice in every power-frequency cycle. The effect on generator rotors is to (tend to) slow them during one part of the cycle and to accelerate them during another part of the cycle. The pulsating torque is strictly true only for single-phase alternators. In three-phase alternators the effect is mutually cancelled in the three phases, since, at any instant the reactive energy supplied on one (or two) phase (s) is equal to the reactive energy being returned on the other two (or one) phase(s) of a balanced system. So that the net result is zero average load on the generators, i.e. the reactive current is wattless'.

An exactly similar phenomenon occurs with shunt capacitive elements in a power system, such as cable capacitance or banks of power capacitors, etc. In this case, energy is stored electrostatically. The cyclic charging and discharging of capacitive plant reacts on the generators of the system in the same manner as that described above for inductive plant, but the current flow to and from capacitive plant is in exact phase opposition to that of the inductive plant. This feature is the basis on which power-factor improvement schemes depend.

It should be noted that while this 'wattless' current (more accurately. the wattless component of a load current) does not draw power from the system, it does cause power losses in transmission and distribution systems by heating the conductors.

In practical power systems, wattless components of load currents are invariably inductive, while the impedances of transmission and distribution systems are predominantly inductively reactive. The combination of inductive current passing through an inductive reactance produces the worst possible conditions of voltage drop (i.e. in direct phase opposition to the system voltage). This results in :

- Transmission power losses
- Voltage drop

The Power-supply authorities reduce the amount of wattless (inductive) current as much as possible.

Figure 5.1 shows that the kVA of apparent Power is the vector sum of the kW of active power and the kVAr of the reactive power.

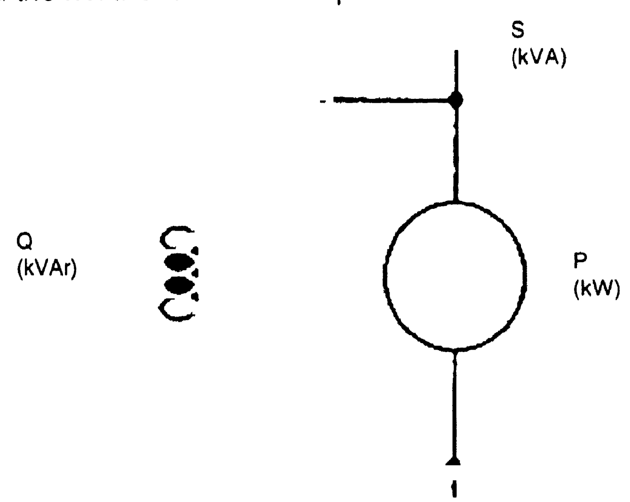


Figure 5.1: An electric motor requires active power P and reactive power Q from the power system.

Wattless (capacitive) currents have the reverse effect on voltage levels and produce voltage-rises in power systems. The power (kW) associated with 'active' energy is usually represented by the letter P. The reactive power (kVAr) is represented by Q. Inductively-reactive power is conventionally positive (+ Q) while capacitively-reactive power is shown as a negative quantity (-Q).

5.2 The Power Factor

The power factor (Pf) is the ratio of kW to kVA. The closer the power factor approaches its maximum possible value of 1, the greater the benefit to consumer and supplier.

$$Pf = \frac{P(kW)}{S(kVA)} = \cos\Phi$$

Where,

P = active power in kW

S = apparent power in kVA

The power factor of a load, which may be a single power-consuming item, or a number of loads collectively (for example an entire installation) is given by the ratio of P/S i.e. kW divided by kVA at any given moment.

Figure 5.2 represents the power diagram of kW vector and the kVA vector. The angular displacement (ϕ) between the two vectors represents the cosine value (Cos ϕ) respectively.

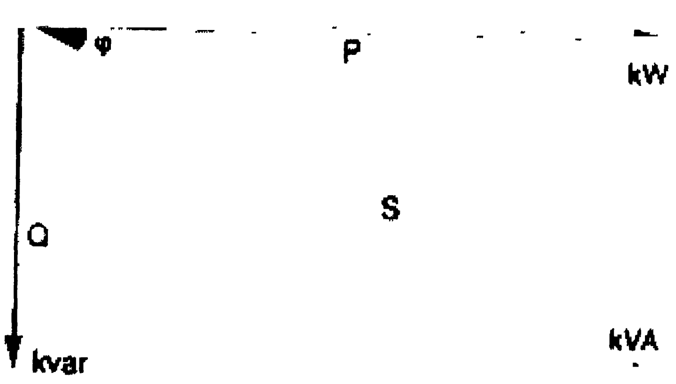


Figure: 5.2 Current and voltage vectors, and derivation of the power diagram

The accuracy of this equivalence depends on an absence of harmonic currents and voltages on the system. It is generally assumed that these effects are small, so that cosΦ and power factor are considered to be exact equivalents for all practical purposes.

A power factor close to unity means that the reactive energy is small compared with the active energy, while a low value of power factor indicates the opposite condition.

Active power (in kW)

- Single phase (1 phase and neutral): $P = V \times I \times \cos\Phi$
- A single phase (phase to phase): $P = U \times I \times \cos\Phi$
- A three phase (3 wires or 3 wires + neutral): $P = \sqrt{3} \times U \times I \times \cos\Phi$

Reactive power (in kVAr)

- single phase (1 phase and neutral) $Q = V \times I \times \sin\Phi$
- single phase (phase to phase) $Q = U \times I \times \sin\Phi$
- three phase (3 wires or 3 wires + neutral): $Q = \sqrt{3} \times U \times I \times \sin\Phi$*

Apparent power (in kVA)

- single phase (1 phase and neutral) $S = V \times I$
- single phase (phase to phase) $S = U \times I$
- three phase (3 wires or 3 wires + neutral): $S = \sqrt{3} \times U \times I$ *

Where,

V: voltage between phase and neutral
U: voltage between phases

$$S = \sqrt{P^2 + Q^2}$$

*for balanced and near-balanced loads on 4-wire systems.

The power 'vector' diagram is a useful artifice, derived directly from the true rotating vector diagram of currents and voltage, as follows:

The power-system voltages are taken as the reference quantities, and one phase only is considered on the assumption of balanced 3-phase loading.

The reference phase voltage (V) is co-incident with the horizontal axis, and the current (I) of that phase will, for practically all power-system loads, lag the voltage by an angle Φ.

The component of I which is in phase with V is the wattful component of I and is equal to $I \times \cos\Phi$, while $V \times I \times \cos\Phi$ equals the kW of power in the circuit, if V is expressed in kV.

The component of I which lags 90 degrees behind V is the wattless component of I and is equal to $I \times \sin\Phi$, while $V \times I \times \sin\Phi$ equals the kVAr of reactive power in the circuit, if V is expressed in kV.

If the vector I is multiplied by V, expressed in kV, then VI equals the kVA for the circuit. The above kW, kVAr and kVA values per phase, when multiplied by 3,

can therefore conveniently represent the relationships of kVA, kW, kVAr and power factor for a total 3-phase load, as shown in figure 5.3.

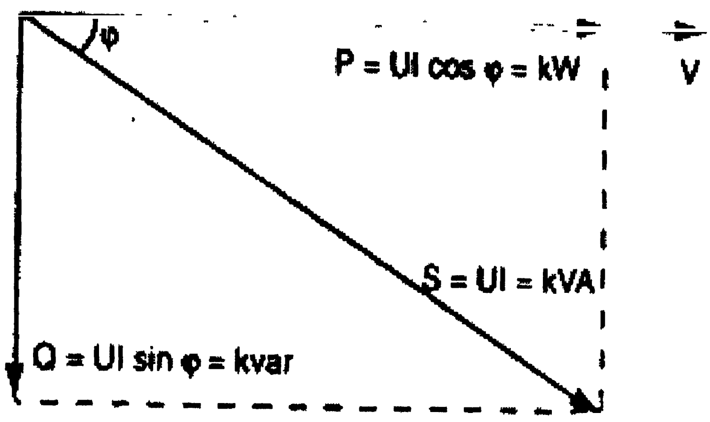


Figure 5.3: Current and Voltage Vector Diagram per Phase

5.3 tanΦ

$$\tan\Phi = \frac{Q}{P} \text{ or } \frac{kVAr}{kW}$$

Some electricity tariffs are partly based on this factor, which shows the amount of reactive power supplied per kW. A low value of tan Φ corresponds to a high power factor and to a favorable consumer bill.

5.4 Plant and Appliances requiring reactive current

All plant and appliances that include electromagnetic devices, or depend on magnetically coupled windings, require some degree of reactive current to create magnetic flux.

Most of the utilisation equipment consume reactive power. Induction motors generally consume reactive power of 65 - 70%, transformers by about 20-25% and cables/over head lines and other switchgear apparatus consume about 10% in a industrial set up.

Loading of the lines, transformers with reactive power increases the voltage losses and hence deviation from nominal value of the system. This impairs the performance of the utilisation equipment and reduces the efficiency of the system.

Moreover, reactive power reduces the handling capacity of all the elements of the system.

Improving the power factor of the operating system reduces the reactive power compensation. This is taken care of by corrective equipments, which supply reactive power to the utilisation equipment and are usually located close to the equipment to reduce power losses in the supply system.

Improvement of power factor of a industry can be grouped under three headings:

a. Methods not related to corrective equipment
b. Methods related to corrective equipment
c. Emergency methods

Power factor can be improved in certain circumstances involving :

1. Streaming of the production process improving the electrical performance of the plant.
2. Replacing induction motors by synchronous motors of equal rating wherever possible.
3. Replacement of underloaded motors with motors of lower rating.
4. Reduction of voltage of motors which are regularly underloaded.
5. Restricting no load operation of motors.
6. Improving motor repair quality.
7. Replacement or relocation of underloaded transformers.

The example below represents the reactive power requirement for a induction motor

Example:

The reactive power drawn by induction motor depends upon the load factor of a motor and its rated power factor.

At rated voltage and rated load motor will draw active power .

$$P_{consumed} = \frac{P_{rated}}{\eta_{rated}}$$

and Reactive power

$$Q_{consumed} = \frac{P_{rated}}{\eta_{rated}} \tan \phi_{rated}$$

Where, η_{rated} = Efficiency of motor at full load
ϕ_{rated} = Phase angle between rated voltage and rated current

The no load power drawn by a motor is given by :

$$Q_{no\ load} = \sqrt{3} \times V_{rated} \times I_{no\ load} \times \text{Sin}\ \phi_{no\ load} \times 10^{-3}\ \text{kVAr}$$

Where, V_{rated} = rated voltage

$I_{no\ load}$ = no load current

$\phi_{no\ load}$ = Phase angle at no load

When the motor load changes from no load to rated value, reactive power consumption also changes from no load reactive power $Q_{no\ load}$ to full load reactive power.

This increase in reactive power consumption is given by:

$$\Delta Q_{rated} = Q_{rated} - Q_{no\ load}$$

$$= \frac{P_{rated}}{\eta_{rated}} \tan \phi_{rated} - \sqrt{3} \times V_{rated} \times I_{no\ load} \times \text{Sin}\ \phi_{no\ load} \times 10^{-3}$$

The increase in reactive power consumption by underloaded motor is proportional to the square of the motor load factor.

$$LF = \frac{P}{P_{rated}} \quad \text{or} \quad \Delta Q = \Delta Q_{rated} \times LF^2$$

Thus, the total reactive power consumed by a induction motor is:

$$Q = Q_{no\ load} + \Delta Q_{rated} \times LF^2\ \text{kVAr}$$

5.5 Practical Measurement Of Power Factor

The power factor (or cos Φ) can be measured, either:

- by a direct-reading cos Φ meter for an instantaneous value, or
- a recording VAr meter, which allows a record over a period of time to be obtained of current, voltage and power factor. Readings taken over an extended period provide a useful means of estimating an average value of power factor for an installation.

5.6 Practical Values of Power Factor

An example in calculation of active and reactive power

Type of circuit	Apparent powers (kVA)	Active power P (kW)	Reactive power Q (kVAr)
Single-phase (phase and neutral) Single-phase (phase to phase)	S=VI S=UI	P=VI cos Φ P = UI cos Φ	Q = VI sin Φ Q = UI sin Φ
Example 5 kW of load Cos Φ = 0.5	10 kVA	5 kW	8,7 kVAr
Three phase 3-wires or 3-wires + netural	S = √3 UI	P = √3 UI cos Φ	Q = √3 UI sin Φ
Example motor Pn=51 kW Cos Φ = 0.86 η = 0.91 (motor efficiency)	65 kVA	56 kW	33 kVAr

The calculations for the three-phase example above are as follows:

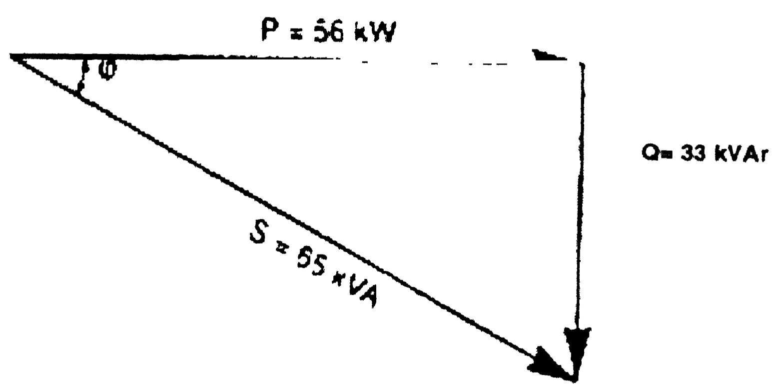


Figure 5.4: Calculation Power Diagram

Pn = delivered shatft power = 51 kW

P = active power consumed = $\frac{Pn}{\eta} = \frac{51}{0.91} = 56\ \text{kW}$

S= apparent power = $\frac{P}{\cos\Phi} = \frac{P}{0.86} = 65\text{kVA}$

The value of tan Φ corresponding to a cos Φ of 0.86 is found to be 0.59 Q = P tan Φ = 56 x 0.59 = 33 kVAr.

Alternatively

$$Q = \sqrt{S^2 - P^2} = \sqrt{65^2 - 56^2} = 33\,kVAr$$

Average power factor values for the most commonly-used plant, equipment and appliances is represented in table 5.1.

Table 5.1: Values of cos Φ and tan Φ for commonly-used plant and equipment

Plant and appliances	Cos Φ	Tan Φ
Common induction motor - loaded at 0%	0.17	5.80
25%	0.55	1.52
50%	0.73	0 94
75%	0.80	0.75
100%	0.85	0.62
Incandescent lamps	1.0	0
Fluorescent lamps (uncompensated)	0.5	1.73
Fluorescent lamps (compensate)	0.93	0 39
Discharge lamps	0.4 to 0.6	2.29 to 1 33
Ovens using resistance elements	1.0	0
Induction heating ovens (compensated)	0.85	0.62
Dielectric type heating ovens	0.85	0.62
Resistance-type soldering machines	0.8 to 0.9	0.75 to 0.48
Fixed 1-phase arc-welding set	0.5	1.73
Arc-welding motor-generating set	0.7 to 0.9	1.02 to 0.48
Arc-welding transformer-rectifier set	0.7 to 0.8	1.02 to 0.75

5.7 Why improve the power factor?

a) Reduction in the cost of electricity

An improvement of the power factor of an Installation presents several technical and economic advantages notably in the reduction of electricity bills.

The installation of power factor correcting capacitors on installations permits the consumer to reduce his electricity bill by maintaining the level of reactive-power consumption below a value contractually agreed with the power supply authority. In this particular tariff, reactive energy is billed according to the tan Φ criterion. As previously noted:

$$\tan\varphi = \frac{Q}{P} = \frac{kVArh}{kWh}$$

At the supply service position, the power supply distributor delivers reactive energy free, until:

- The point at which it reaches 48% of the active energy (tan Φ = 0.48) for a maximum period of 16 hours each day (from 06-00 h to 22-00 h) during the most-heavily loaded period in summer, from the 1st of April until the 31st of October.
- Without limitation during light-load periods in winter and during the entire period from November until the 31st of March.

During the periods of limitation, reactive-energy consumption exceeding 40% of the active energy (i.e. tan Φ> 0.48) is billed monthly at the current rates.

Thus, the quantity of reactive energy billed in these periods will be:

kVArh (to be billed) = kWh (tan Φ - 0.48) where kWh is the active energy consumed during the periods of limitation and kWh tan Φ is the total reactive energy during a period of limitation, and 0.4 kWh is the amount of reactive energy delivered free during a period of limitation.

tan Φ = 0.48 corresponds to a pf of 0.90 so that, if steps are taken to ensure that during the limitation periods the pf never fails below 0.90, the consumer will have nothing to pay for the reactive power consumed.

Against the financial advantages of reduced billing, the consumer must balance the cost of purchasing, installing and maintaining the power factor improvement capacitors and controlling switchgear, automatic control equipment (where stepped levels of compensation are required) together with the additional kWh consumed by the dielectric losses of the capacitors, etc.

It may be found that it is more economic to provide partial compensation only, and that paying for some of the reactive energy consumed is less expensive than providing 100% compensation.

The question of power factor correction is always a matter of optimisation, except in very simple cases.

b) Technical / Economical Optimization

Power factor improvement allows the use of smaller transformers, switchgear and cables, etc. as well as reducing power losses and voltage drop in an installation.

A high power factor allows the optimization of the components of an installation. Overrating of certain equipment can be avoided, but to achieve the best results the correction should be effected as close to the individual items of inductive plant as possible.

- **Reduction of cable size**

Table below shows the required increase in the size of cables as the power factor is reduced from unity to 0.4 i.e. multiplying factor for cable size as a function of cosΦ.

Multiplying factor for the cross-sectional area of the cable core(s)	1	1.25	1.67	2.5
cos Φ	1	0.8	0.6	0.4

- **Reduction of losses (kW) in cables (Distribution losses)**

Losses in cables are proportional to square of the current and are measured by the kWh meter for the installation. Reduction of the total current in a conductor by 10% for example, will reduce the losses by almost 20%.

- **Reduction of voltage drop**

pf correction capacitors reduce or even cancel completely the (inductive) reactive current in upstream conductors, thereby reducing or eliminating voltage drops.

Note: Overcompensation will produce a voltage rise at the capacitors.

- **Increase in available power**

By improving the power factor of a load supplied from a transformer, the current through the transformer will be reduced thereby allowing more loads to be added. In practice, it may be less expensive to improve the power factor, than to replace the transformer by a larger unit.

5.8 How to improve the power factor?

a) Theoretical principles

Improving the power factor of an installation requires a bank of capacitors, which acts as a source of reactive energy. This arrangement is said to provide reactive energy compensation.

Figure 5.5 uses the power diagram discussed in figure 5.2 to illustrate the principle of compensation by reducing a large reactive power Q to a smaller value Q' by means of a bank of capacitors having a reactive power Qc.

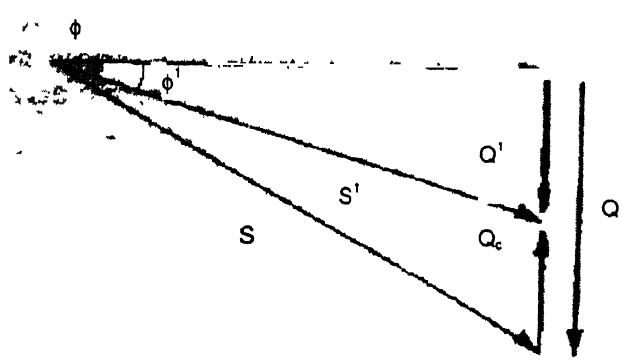


Figure 5.5: Diagram showing the principle of compensation
$Q_c = P(\tan\varphi - \tan\varphi')$

In doing so, the magnitude of the apparent power S is seen to reduce to S'.

Example :

A motor consumes 100 kW at a pf of 0.75 (i.e. tan Φ = 0.88).
To improve the pf to 0.93 (i.e. tan Φ = 0.4),
The reactive power of the capacitor bank must be: $Q_C = 100\,(0.88 - 0.4) =$ 48 kVAr

The selected level of compensation and the calculation of rating for the capacitor bank, depend on the particular installation.

Note: Before embarking on a compensation project, a number of precautions should be observed. In particular, oversizing of motors should be avoided, as well as the operation of the motors in an unloaded condition.

b) By using what equipment?

Compensation can be carried out by a fixed value of capacitance in favorable circumstances. Sometimes compensation is more-commonly effected by means of an automatically controlled stepped bank of capacitors.

Note: When the installed reactive power of compensation exceeds 800 kVAr, and the load is continuous and stable it is often found to be economically advantageous to install capacitor banks at high voltage.

Compensation at L.V.

At low voltage, compensation is provided by:
- fixed-valued capacitor;
- equipment providing automatic regulation, or banks which allow continuous adjustment according to requirements, as loading of the installation changes.

- **Fixed Capacitors**

  This arrangement employs one or more capacitor(s) to form a constant level of compensation. Control may be:

  - manual: by circuit breaker or load-break switch;
  - semi-automatic: by contactor;
  - direct connection to an appliance and switched with it.

  These capacitors are applied:
  - at the terminals of inductive devices 1 (motors and transformers)
  - at busbars supplying numerous small motors and inductive appliance for which individual compensation would be too costly;
  - in cases where the level of load is reasonably constant.

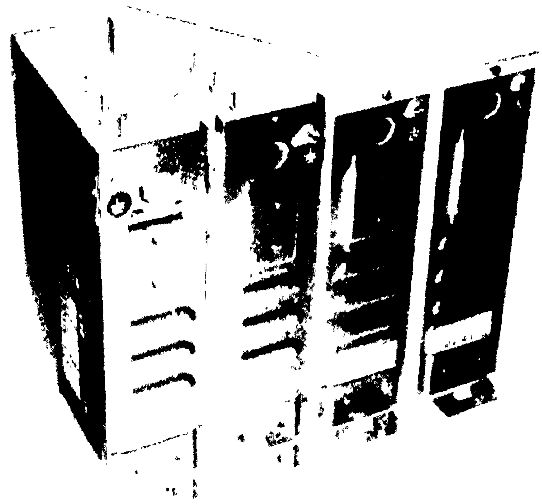


Figure 5.6: Example of fixed-value-compensation capacitors.

- **Automatic Capacitor Banks**

This kind of equipment provides automatic control of compensation, maintaining within close limits, a selected level of power factor. Such equipment is applied at points in an installation where the active-power and / or reactive-power variations are relatively large, for example:

- at the busbars of a general power distribution board,
- at the terminals of a heavily-loaded feeder cable

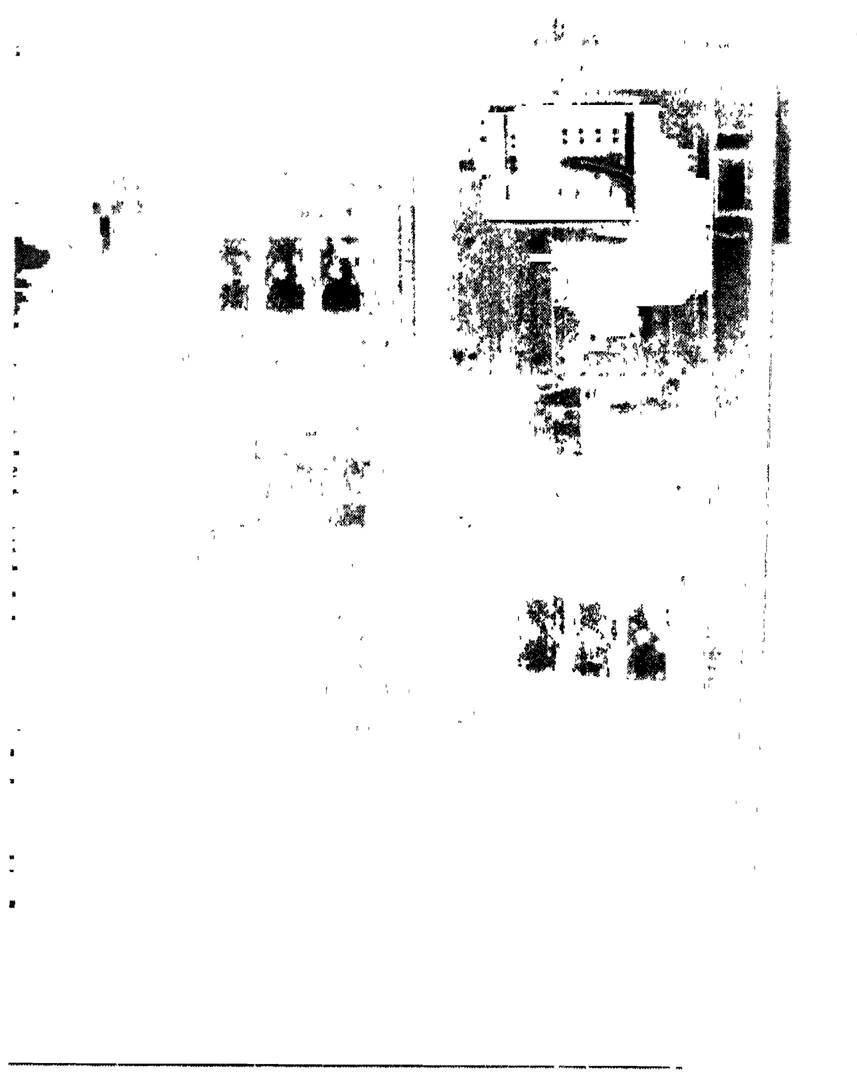


Figure 5.7: Example of automatic-compensation-regulating equipment

5.9 The Principles of and Reasons for using Automatic Compensation

Automatically- regulated banks of capacitors allow an immediate adaptation of compensation to match the level of load.

A bank of capacitors is divided into a number of sections, each of which is controlled by a contactor. Closure of a contactor, switches its section into parallel operation with other sections already in service. The size of the bank can therefore be increased or decreased in steps, by the closure and opening of the controlling contactors. A control relay monitors the power factor of the

controlled circuit(s) and is arranged to close and open appropriate contactors to maintain a reasonably constant system power factor (within the tolerance imposed by the size of each step of compensation). In recent times the use of thyristor is gaining momentum. The current transformer for the monitoring relay must evidently be placed on one phase of the incoming cable which supplies the circuit(s) being controlled, as shown in figure-5.8. By closely matching compensation to that required by the load, the possibility of producing over-voltages at times of low load will be avoided, thereby preventing a potentially dangerous condition and possible damage to appliances and equipment.

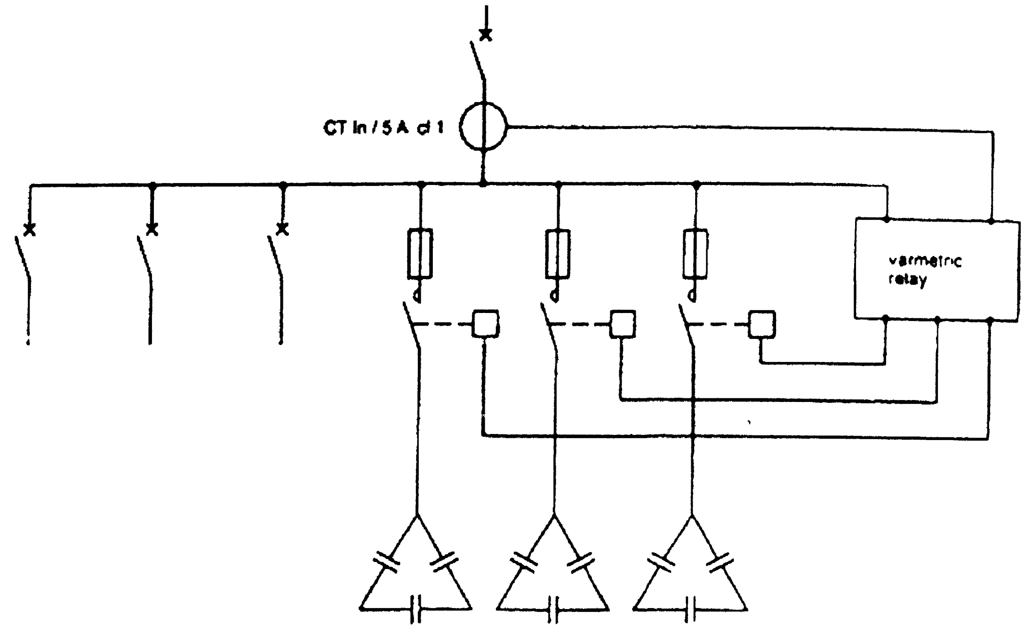


Figure 5.8: Principle of automatic-compensation control.

5.10 The choice between a fixed or automatically regulated bank of capacitors commonly applied rules

Where the kVAr rating of the capacitors is less or equals to 15% of the supply-transformer rating, a fixed value of compensation is appropriate.

Above the 15% level it is advisable to install an automatically controlled bank of capacitors.

The location of low-voltage capacitors in an installation constitutes the mode of compensation, which may be global (one location for the entire installation), partial (section-by-section), local (at each individual device), or some combination of the latter two. In principle, the ideal compensation is applied at a point of consumption and at the level required at any instant.

In practice, technical and economic factors govern the choice.

5.11 Where to install correction capacitors?

a) Global Compensation

Where a load is continuous and stable, global compensation can be applied.

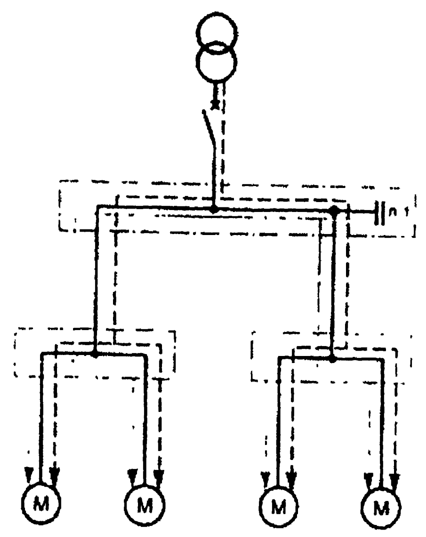


Figure 5.9: Global Compensation

Principle

The capacitor bank is connected to the busbars of the main LV distribution board for the installation, and remains in service during the period of normal load.

Advantages

The global type of compensation:

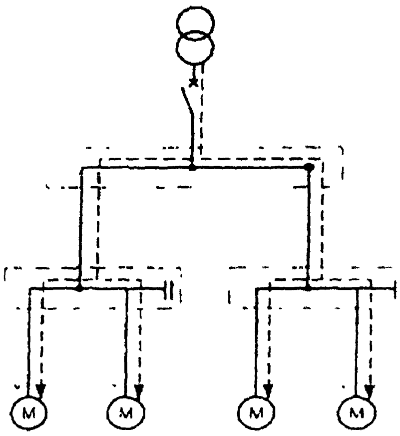
- reduces the tariff penalties for excessive consumption of kVAr;
- reduces the apparent power kVA demand, on which standing charges are usually based;
- relieves the supply transformer, which is then able to accept more load it necessary.

Comments

- reactive current still flows in all conductors cables leaving (i.e. downstream of) the main LV distribution board;
- For the above reason, the sizing of these cables, and power losses in them, are not improved by the global mode of compensation.

b) Compensation By Sector

Compensation by sector is recommended when the installation is extensive, and where the load/time patterns differ from one part of the



installation to another.

Figure 5.10 : Compensation by sector

Principle

Capacitor banks are connected to busbars of each local distribution board, as shown in Figure 5.10.

A significant part of the installation benefits from this arrangement. Notably the feeder cables from the main distribution board to each of the local distribution boards at which the compensation measures are applied.

Advantages

The compensation by sector:

- reduces the tariff penalties for excessive consumption of kVArs
- reduces the apparent power kVA demand on which standing charges are usually based
- relieves the supply transformer, which is then able to accept more load if necessary
- the size of the cables supplying the local distribution boards may be reduced, or will have additional capacity for possible load increases:
- losses in the same cables will be reduced.

Comments

- reactive current still flows in all cables downstream of the local distribution boards;
- for the above reason, the sizing of these cables, and the power losses in them, are not improved by compensation by sector:
- where large changes in loads occur, there is always a risk of overcompensation and consequent over-voltage problems

c) Individual Compensation

Individual compensation should be considered when the power of motor is significant with respect to power of the installation.

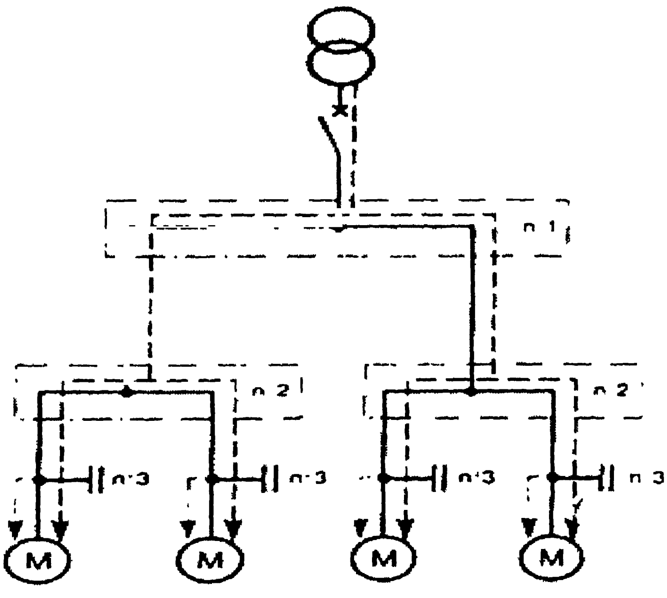


Figure 5.11: Individual compensation

Principle

Capacitors are connected directly to the terminals of inductive plant. Individual compensation should be considered when the power of the motor is significant with respect to the declared power requirement (kVA) of the installation.

The kVAr rating of the capacitor bank is in the order of 25% of the kW rating of the motor. Table 5.2 gives the guidelines to select suitable capacitor (kVAr) requirement for various ratings of induction motor. Complementary compensation at the origin of the installation (transformer) may also be beneficial.

Advantages

Individual compensation:

- reduces the tariff penalties for excessive consumption of kVAr;
- reduces the apparent power kVA demand;
- reduces the size of all cables as well as the cable losses.

Comments

- significant reactive currents no longer exist in the installation.

5.12 How to Decide the Optimum Level of Compensation?

a) General Method

Listing of reactive power demands at the design stage

The levels of active and reactive power loading, at each level of the installation (generally at points of distribution and sub-distribution of circuits) can be determined.

Technical-Economic optimization for an existing installation

The optimum rating of compensation capacitors for an existing installation can be determined from the following principal considerations:

- Electricity bills prior to the installation of capacitors;
- Future electricity bills anticipated following the installation of capacitors;
- At cost of purchase of capacitors & control equipment (contactors, relaying, cabinets, etc.) and
- Installation and maintenance costs.

b) Simplified Method

General Principle

An approximate calculation is generally adequate for most practical cases, and may be based on the assumption of a power factor of 0.8 (lagging) before compensation. In order to improve the power factor to a value sufficient to avoid tariff penalties (this depends on local tariff structures, but is assumed here to be 0.93) and to reduce losses, volt-drops, etc. in the installation, reference can be made to Table 5.3.

Table 5.2 : Recommended capacitor rating for direct connection to induction motors (To improve power factor to 0.95 or better)

Motor H.P.	Capacitor rating in KVAr when motor speed is:						Motor H.P.	Capacitor rating in KVAr when motor speed is:					
	3000 r.p.m	1500 r.p.m	1000 r.p.m	750 r.p.m	600 r.p.m	500 r.p.m		3000 r.p.m	1500 r.p.m	1000 r.p.m	750 r.p.m	600 r.p.m.	500 r.p.m.
2.5	1	1	1.5	2	2 5	2.5	105	22	24	27	29	36	41
5	2	2	2.5	3.5	4	4	110	23	25	28	30	38	43
7.5	2 5	3	3.5	4.5	5	5.5	115	24	26	29	31	39	44
10	3	4	4.5	5.5	6	6.5	120	25	27	30	32	40	46
12.5	3.5	4.5	5	6.5	7.5	8	125	26	28	31	33	41	47
15	4	5	6	7.5	8.5	9	130	27	29	32	34	43	49
17.5	4 5	5.5	6.5	8	10	10.5	135	28	30	33	35	44	50
20	5	6	7	9	11	12	140	29	31	34	36	46	52
22 5	5 5	6 5	8	10	12	13	145	30	32	35	37	47	54
25	6	7	9	10 5	13	14.5	150	31	33	36	38	48	55
27 5	6.5	7.5	9.5	11.5	14	16	155	32	34	37	39	49	56
30	7	8	10	12	15	17	160	33	35	38	40	50	57
32.5	7.5	8.5	11	13	16	18	165	34	36	39	41	51	59
35	8	9	11 5	13.5	17	19	170	35	37	40	42	53	60
37.5	8 5	9.5	12	14	18	20	175	36	38	41	43	54	61
40	9	10	13	15	19	21	180	37	39	42	44	55	62
42 5	9.5	11	14	16	20	22	185	38	40	43	45	56	63
45	10	11.5	14.5	16.5	21	23	190	38	40	43	45	58	65
47.5	10.5	12	15	17	22	24	195	39	41	44	46	59	66
50	11	12 5	16	18	23	25	200	40	42	45	47	60	67
55	12	13.5	17	19	24	26	205	41	43	46	48	61	68
60	13	14..5	18	20	26	28	210	42	44	47	49	61	69
65	14	15.5	19	21	27	29	215	42	44	47	49	62	70
70	15	16 5	20	22	28	31	220	43	45	48	50	63	71
75	16	17	21	23	29	32	225	44	46	49	51	64	72
80	17	19	22	24	30	34	230	45	47	50	52	65	73
85	18	20	23	25	31	35	235	46	48	51	53	65	74
90	19	21	24	26	33	37	240	46	48	51	53	66	75
95	20	22	25	27	34	38	245	47	49	52	54	67	75
100	21	23	26	28	35	40	250	48	50	53	55	68	76

Note . The recommended capacitor rating given in the above table are only for guidance purpose.(The capacitor rating should correspond approximately to the apparent of the motor on no-load).

Table 5.3 : Multiplying factor for calculating the sizes of capacitor for power factor improvement

Power facto r of load before applying capacitors	Size of capacitors in kVAr per kW of load for raising the power factor to											
	0.80	0.85	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	Unity
0.45	1.230	1.360	1.501	1.532	1.561	1.592	1.626	1.659	1.695	1.737	1.784	1.846	1.988
0.46	1.179	1.309	1.446	1.473	1.502	1.533	1.567	1.600	1.636	1.677	1.725	1.786	1.929
0.47	1.130	1.260	1.397	1.425	1.454	1.485	1.519	1.552	1.588	1.629	1.677	1.758	1.881
0.48	1.076	1.206	1.343	1.370	1.400	1.430	1.464	1.497	1.534	1.575	1.623	1.684	1.826
0.49	1.030	1.160	1.297	1.326	1.355	1.386	1.420	1.453	1.489	1.530	1.578	1.639	1.782
0.50	0 982	1 112	1.248	1.276	1.303	1.337	1.369	1.403	1 441	1 481	1.529	1 590	1.732
0.51	0 936	1 066	1 202	1 230	1.257	1.291	1 323	1 357	1 395	1 435	1 483	1 544	1 686
0.52	0.894	1.024	1 160	1.188	1.215	1 249	1 281	1 315	1 353	1 393	1 441	1 502	1 644
0.53	0.850	0.980	1 116	1 144	1 171	1 205	1 237	1 271	1 309	1 349	1 397	1 458	1 600
0.54	0 809	0.939	1 075	1 103	1.130	1 164	1 196	1 230	1 268	1 308	1 356	1 417	1 559
0.55	0 769	0 899	1 035	1 063	1 090	1 124	1 156	1 190	1 228	1 268	1 316	1 377	1 519
0.56	0 730	0.860	0 996	1.024	1.051	1 085	1 117	1 151	1 189	1 229	1 277	1 338	1 480
0.57	0 692	0 822	0 958	0 986	1 013	1.047	1 079	1 113	1 151	1 191	1 239	1 300	1 442
0.58	0 655	0.785	0 921	0 949	0.976	1.010	1 042	1 076	1 114	1 154	1 202	1 263	1 405
0.59	0 618	0 748	0 884	0 912	0 939	0 973	1 005	1 039	1 077	1 117	1 165	1 226	1 368
0.60	0 584	0 714	0 849	0.878	0 905	0 939	0 971	1 005	1 043	1 083	1 131	1 192	1 334
0.61	0 549	0 679	0.815	0 843	0 870	0.904	0 936	0 970	1 008	1 048	1 096	1 157	1.299
0.62	0 515	0.645	0 781	0 809	0 836	0.870	0 902	0 936	0 974	1 014	1 062	1 123	1 265
0.63	0 483	0 613	0 749	0 777	0 804	0.838	0 870	0 904	0 942	0 982	1 030	1 091	1 233
0.64	0 450	0.580	0 716	0 744	0 771	0 805	0 837	0 871	0 909	0 949	0 997	1 058	1 200
0.65	0 419	0 549	0 685	0 713	0.740	0 774	0 806	0 840	0 878	0 918	0 966	1 027	1 169
0.66	0 388	0 518	0.654	0 682	0 709	0 743	0 775	0 809	0 847	0 887	0 935	0 996	1 138
0.67	0 358	0 488	0 624	0 652	0 679	0 713	0 745	0 779	0 817	0 857	0 905	0 966	1 108
0.68	0 329	0 459	0.595	0 623	0 650	0 684	0 716	0 750	0 788	0 828	0 876	0 937	1 079
0.69	0 299	0 429	0.565	0 593	0.620	0 654	0 686	0 720	0 758	0 798	0 840	0 907	1 049
0.70	0 270	0 400	0.536	0 564	0.591	0 625	0 657	0 691	0 729	0 769	0 811	0 878	1.020
0.71	0 242	0 372	0.508	0.536	0.563	0.597	0 629	0 663	0 701	0 741	0 783	0 850	0 992
0 72	0 213	0 343	0.479	0.507	0 534	0 568	0 600	0 634	0 672	0 712	0 754	0 821	0 963
0.73	0 186	0.316	0 452	0 480	0 570	0 541	0 573	0 607	0 645	0 685	0 727	0 794	0 936
0.74	0 159	0 289	0 425	0 453	0.480	0 514	0 546	0 580	0 618	0 658	0 700	0 767	0 909
0.75	0.132	0 262	0 398	0 426	0 453	0 487	0 519	0 553	0 591	0 631	0 673	0 740	0 882
0.76	0 105	0 235	0.371	0.399	0 426	0 460	0 492	0 526	0 564	0 604	0 652	0 713	0 855
0.77	0 079	0 209	0 345	0 373	0 400	0 434	0 466	0 500	0 538	0 578	0 620	0 687	0 829
0.78	0 053	0 183	0 319	0 347	0 374	0 408	0 440	0 474	0 512	0 552	0 594	0 661	0 803
0.79	0 026	0 156	0.292	0 320	0 347	0 381	0 413	0 447	0 485	0 525	0 567	0 634	0 776
0.80	-	0 130	0 266	0 294	0 321	0 355	0 387	0 421	0 459	0 499	0 541	0 608	0 750
0 81		0 104	0 240	0 268	0 295	0 329	0 361	0 395	0 433	0 473	0 515	0 582	0 724
0 82		0 078	0 214	0.242	0 269	0 303	0 335	0 369	0 407	0 447	0 489	0 556	0 698
0 83		0 052	0 188	0 216	0 243	0 277	0 309	0 343	0 381	0 421	0 463	0 530	0 672
0 84		0 026	0 162	0 190	0 217	0 251	0.283	0 317	0 355	0 395	0 437	0 504	0 645
0.85		-	0 136	0 164	0 191	0 225	0 257	0 291	0 329	0 369	0 417	0 478	0 620
0.86		-	0 109	0 140	0 167	0 198	0 230	0 264	0 301	0 343	0 390	0 450	0 593
0 87			0 083	0 114	0 141	0 172	0 204	0 238	0 275	0 317	0 364	0 424	0 567
0.88		-	0 054	0 085	0 112	0 143	0 175	0 209	0 246	0 288	0 335	0 395	0 538
0 89			0 028	0 059	0 836	0 117	0 149	0 183	0 230	0 262	0 309	0 369	0 512
0.90		-	-	0 031	0 058	0 089	0 121	0 155	0 192	0 234	0 281	0 341	0 484
0.91					0 027	0 058	0 090	0 124	0 161	0 203	0 250	0 310	0 453
0 92						0 031	0 063	0 097	0 134	0 176	0 223	0 283	0 426
0 93							0 032	0 066	0 103	0 145	0 192	0 252	0 395
0 94								0 034	0 071	0 113	0 160	0 220	0 363
0 95		-							0 037	0 079	0 126	0 186	0 329
0 96		-								0 042	0 089	0 149	0 292
0 97											0 047	0 107	0 250
0.98			-									0 060	0 203
0 99													0 143

Example : *Given 100 kW load to be improved from 0 77 to 0 95 Power Factor Factor from table is 0 500*
Capacitor required (kVAr) = 100 x 0 500 = 50 kVAr

From the table 5.3, it can be seen that, to raise the power factor of the installation from 0.8 to 0.93 will require 0.355 kVAr per kW of load. The rating of a bank of capacitors at the busbars of the main distribution board of the installation would be Q(kVAr) = 0.355 x P (kW).

This simple approach allows a rapid determination of the compensation capacitors required, in the global, partial or independent mode.

Example

It is required to improve the power factor of a 666 kVA installation from 0.75 to 0.928.

The active power demand is 666 x 0.75 = 500 kW.

In table 16 the intersection of the row cos Φ = 0.75 (before correction) with the column

cos Φ = 0.93 (after correction) indicates a value of 0.487 kVAr of compensation per kW of load.

For a load of 500 kW therefore, 500 x 0.487 = 244 kVAr of capacitive compensation is required.

Note: this method is valid for any voltage level. i.e. is independent of voltage.

c) Method Based on the Avoidance of Tariff Penalties

In the case of certain common types of tariff, an examination of several bills covering the most heavily-loaded period of the year, allows determination of the kVAr level of compensation required to avoid kVArh (reactive-energy) charges.

The pay-back period of a bank of power-factor-improvement capacitors and associated equipment is generally about 18 months.

The following method allows calculation of the rating of a proposed capacitor bank, based on billing details covering the loaded period. The method determines the minimum compensation required to avoid these charges which are based on kVArh consumption.

The procedure is as follows:

- Refer to the bills covering consumption for the 5 months of winter heavily loaded period of the year.
- Identify the line on the bills referring to 'reactive-energy consumed' and 'kVArh to be charged'. Choose the bill, which shows the highest charge for kVArh (after checking that this was not due to some exceptional situation).
- For example: 15.966 kVArh in April.
- Evaluate the total period of loaded operation of the installation for that month, for instance: 220 hours (22 days x 10 hours). The hours, which must be counted are those occurring during the heaviest load and the highest peak loads occurring on the power system. These are given in the tariff documents, and are (commonly) during a 16-hour period each day, either from 06.00 H to 22.00 H or from 07.00 H to 23.00 H according to the region. Outside these periods, no charge is made for kVArh consumption.
- the necessary value of compensation in kVAr

$$\text{in kVAr} = \frac{\text{kVArh billed}}{\text{number of hours of operation}} = Qc$$

in the billing period, during the hours of which reactive energy is charged for the

$$Qc = \frac{15.966\ \text{kVArh}}{220\ \text{h}} = 73\ \text{kVAr}$$

case considered above.

The rating of the installed capacitor bank is generally chosen to be slightly larger than that calculated.

5.13 Method Based on Reduction of Declared Maximum Apparent Power (kVA)

For 2-part tariffs based partly on a declared value of kVA, a table - 5.3 allows determination of the kVAr of compensation required to reduce the value of kVA declared, and to avoid exceeding it.

For consumers whose tariffs are based on a fixed charge per kVA declared. plus a charge per kWh consumed; it is evident that a reduction in declared kVA would be beneficial.

Figure 5.12 shows that as the power factor improves, the kVA value diminishes for a given value of kW (P).

The improvement of the power factor is aimed at (apart from other advantages previously mentioned) reducing the declared level and never exceeding it, thereby avoiding the payment of an excessive price per kVA during the periods of excess, and / or tripping of the main circuit breaker. Table 5.3 indicates the value of kVAr of compensation per kW of load, required to improve from one value of power factor to another.

Example:
A supermarket has a declared load of 122 kVA at a power factor of 0.7 lagging. i.e. an active-power load of 85.4 kW.

The particular contract for this consumer was based on stepped values of declared kVA (in steps of 6 kVA up to 108 kVA, and 12 kVA steps above that value. this is a feature in many types of two-part tariff). In the case being considered, the consumer was billed on the basis of 132 kVA.

Referring to table A, it can be seen that a 60 kVAr bank of capacitors will improve the power factor of the load from 0.7 to 0.95 (O.691 x 85.4 = 59 kVAr in the table). The declared value of kVA will then be

85.4 /0.95 = 90 kVA an improvement of 30%.

$\cos\phi = 0.7$
$\cos\phi = 0.95$
S =12 kVA
S^1 = 90 kVA
Q = 87 kVAr
Qc = 59 kVAr
Q^1 = 28.1 kVAr

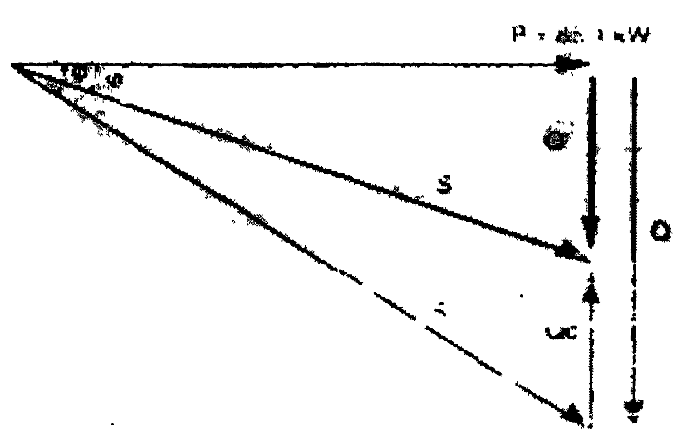


Figure 5.12: Reduction of declared maximum kVA by power factor improvement

5.14 Compensation at the Terminals of a Transformer

a) Compensation to increase the available active power output

The installation of a bank of capacitors can avoid the need to change a transformer in the event of a load increase.

Steps similar to those taken to reduce the declared maximum kVA. i.e. improvement of the load power factor, as discussed in sub-clause 5.12, will maximize the available transformer capacity, i.e. to supply more active power.

Cases can arise where the replacement of a transformer by a larger unit, to cater for load growth, may be avoided by this means. Table-5.4 shows directly the power (kW) capability of fully-loaded transformers at different load power factors, from which the increase of active-power output, as the value of power factor increases, can be obtained.

Table 5.4 : Active Power Capability Of Fully Loaded Transformers, When Supplying Loads at Different Values of Power Factor

Tan ϕ	Cos ϕ	Nominal kVA rating of transformers											
		100	160	250	315	400	500	630	800	1000	1250	1600	2000
0.00	1	100	160	250	315	400	500	630	800	1000	1250	1600	2000
0.20	0.98	98	157	245	309	392	490	617	784	980	1225	1568	1960
0.29	0.96	96	154	240	302	384	480	605	768	960	1200	1536	1920
0.36	0.94	94	150	235	296	376	470	592	752	940	1175	1504	1880
0.43	0.92	92	147	230	290	368	460	580	736	920	1150	1472	1840
0.48	0.90	90	144	225	284	360	450	567	720	900	1125	1440	1800
0.54	0.88	88	141	220	277	352	440	554	704	880	1100	1408	1760
0.59	0.86	86	138	215	271	344	430	541	688	860	1075	1376	1720
0.65	0.84	84	134	210	265	336	420	529	672	840	1050	1344	1680
0.70	0.82	82	131	205	258	328	410	517	656	820	1025	1312	1640
0.75	0.80	80	128	200	252	320	400	504	640	800	1000	1280	1600
0.80	0.78	78	125	195	246	312	390	491	624	780	975	1248	1560
0.86	0.76	76	122	190	239	304	380	479	608	760	950	1216	1520
0.91	0.74	74	118	185	233	296	370	466	592	740	925	1184	1480
0.96	0.72	72	115	180	227	288	360	454	576	720	900	1152	1440
1.02	0.70	70	112	175	220	280	350	441	560	700	875	1120	1400

Example :

An installation is supplied from a 630 kVA transformer loaded at 450 kW (P1) with a mean power factor of 0.8 lagging (Refer to Figure 5.13).

The apparent power = $S_1 = \frac{450}{0.8} = 562\,\text{kVA}$

The corresponding reactive power = $Q_1 = \sqrt{S_1^2 - P_1^2} = 337\,\text{kVAr}$

The anticipated load increase P_2 = 100 kW at a power factor of 0.7 lagging.

The apparent power S_2 = 100/0.7 = 143 kVA

The corresponding reactive power = $Q_2 = \sqrt{S_2^2 - P_2^2} = 102\,\text{kvar}$

What is the minimum value of capacitive kVAr is to be installed, in order to avoid a change of transformer?

Total power now to be supplied:

P = PI + P2 = 550 kW.

The maximum reactive power capability of the 630 kVA transformer when delivering 550 kW is:

$$Qm = \sqrt{S^2 - P^2}$$

$$Qm = \sqrt{630^2 - 550^2} = 307\ \text{kvar}$$

Total reactive power required by the installation before compensation: $Q_1 + Q_2$ = 337 + 102 = 439 kVAr.

So that the minimum size of capacitor bank to install:

QkVAr = 439 - 307 = 132 kVAr.

It should be noted that this calculation has not taken account of peak loads and their duration.

The best possible improvement, i.e. correction that attains a pf of 1 would permit a power reserve for the transformer of 630 - 550 = 80 kW. The capacitor bank would then have to be rated at 439 kVAr.

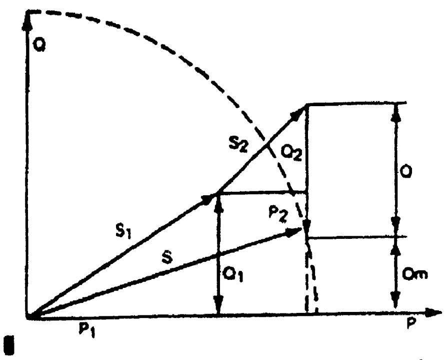


Figure 5.13: Compensation Q allows the installation-load extension S_2 to be added, without the need to replace the existing transformer, the output of which is limited to S.

b) Compensation Of Reactive Energy Absorbed By The Transformer

Where metering is carried out at the HV side of a transformer, the reactive-energy losses in the transformer may (depending on the tariff) need to be compensated.

The nature of transformer inductive reactance

All previous references have been to shunt connected devices such as those used in normal loads and pf-correcting capacitor banks etc. The reason for this, is that shunt-connected plant requires (by far) the largest quantities of reactive energy in power systems; however, series-connected reactances, such as the inductive reactances of power lines and the leakage reactance of transformer windings, etc. also absorb reactive energy.

Where metering is carried out at the HV side of a transformer, the reactive energy losses in the transformer may (depend on the tariff) need to be compensated.

As far as reactive energy losses only are concerned, the elementary diagram of Figure 5.14 may represent a transformer. All reactance values are referred to the secondary side of the transformer, where the shunt branch represents the magnetizing current path. The magnetizing current remains practically constant (at about 1.8 % of full-load current)

from no load to full load in normal circumstances, i.e. with a constant primary voltage, so that a shunt capacitor of fixed value can be installed at the HV or LV side, to compensate for the reactive energy absorbed.

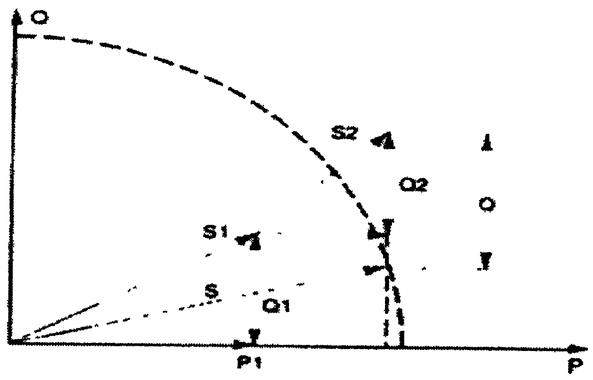


Figure 5.14: Transformer reactances (per phase).

The reactive power absorbed by a transformer cannot be neglected, and can amount to (about) 5% of the transformer rating when supplying its full load.

In transformers, both shunt (magnetizing) and series (leakage flux) reactances absorb reactive power. A bank of shunt-connected LV capacitors can provide complete compensation.

c) Reactive-Power absorption in series-connected (leakage flux) reactance

The equivalent circuit diagram for transformer in figure-5.15 gives a simple illustration of this phenomenon. The reactive-current component through the load = I sin φ so that $kVAr_L$ = VI sin φ

The reactive-current component from the source = I sin φ^1 so that $kVAr_s$ =EI sinφ^1.

Where,

V and E are expressed in kV.

It can be seen that E > V and sin φ^1 > sin φ The difference between EI sin ($\varphi^1$and VI sin (φ gives the kVAr per phase absorbed by X_L.

It can be shown that this kVAr value is equal to I^2X_L (which is analogous to the I^2R active-power (kW) losses due to the series resistance of power lines, etc.).

From the I^2X_L formula it is very simple to deduce the kVAr absorbed at any load Value for a given transformer, as follows:

If per-unit values are used (instead of percentage values) direct multiplication of I and X_L can be carded out.

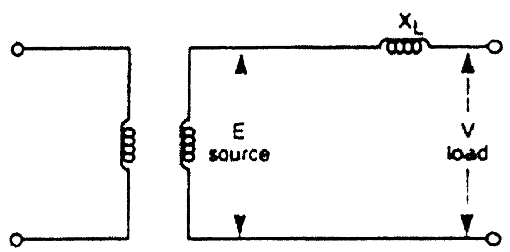


Figure 5.15: Reactive power absorption by series inductance.

Example:

A 630 kVA transformer with a short-circuit reactance voltage of 4% is fully loaded. What is its reactive-power (kVAr) loss?
0.04 pu IPU = 1

loss = $I^2X_L = 1^2$ X 0.04 = 0.04 pu kVAr

where,

1 pu = 630 kVA

The 3-phase kVAr losses are 630 x 0.04 = 25.2 kVAr (or, quite simply, 4% of 630 kVA).

At half load i.e. I = 0.5 pu the losses will be 0.51 x 0.04 = 0.01 pu = 630 x 0.01 = 6.3 kVAr and so on...

This example illustrates that:

- the power factor at the primary side of a loaded transformer is different (normally lower) than that at the secondary side (due to the absorption of vars).

- that full-load kVAr losses due to leakage reactance are equal to the transformer percentage reactance (4% reactance means a kVAr loss equal to 4% of the kVA rating of the transformer),
- that kVAr losses due to leakage reactance vary according to the current (or kVA loading) squared.

To determine the total kVAr losses of a transformer the constant magnetizing-current circuit losses (approx. 1.81% of the transformer kVA rating) must be added to the foregoing "series" losses.

Table 5.5 shows the no-load and full load kVAr losses for typical distribution transformer.

In principle, series inductances can be compensated by fixed series capacitors (as is commonly the case for long HV transmission lines). This arrangement is operationally difficult. However, so that, at the voltage levels covered by this guide, shunt compensation is always applied.

In the case of HV metering, it is sufficient to raise the power factor to a point where the transformer plus load reactive-power consumption is below the level at which a billing charge is made. This level depends on the tariff, but often corresponds to a tanΦ value of 0.31 (cosΦ of 0.955)

As a matter of interest, the kVAr losses in a transformer can be completely compensated by adjusting the capacitor bank to give the load a (slightly) leading power factor. In such a case all of the kVAr of the transformer is being supplied from the capacitor bank, while the input to the HV side of the transformer is at unity power factor, as shown in Figure 5.16.

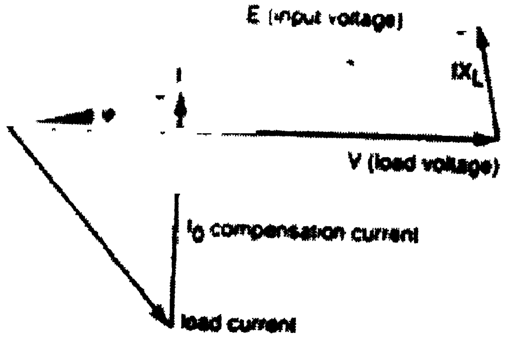


Figure 5.16: Overcompensation of load to completely compensate transformer reactive-power losses.

In practical terms, therefore, compensation for transformer-absorbed kVAr is included in the capacitors primarily intended for power-factor correction of the load, either globally; partially; or in the individual mode.

Unlike most other kVAr-absorbing items, the transformer absorption (i.e. the part due to the leakage reactance) changes significantly with variations of load level, so that, if individual compensation is applied to the transformer, then an average level of loading will have to be assumed.

Fortunately, this kVAr consumption generally forms only a relatively small part of the total reactive power of an installation, and so mismatching of compensation at times of load change is not likely to be a problem. Table-5.5 indicates typical kVAr loss values for the magnetizing circuit ('no-load kVAr' columns), as well as for the total losses at full load, for a standard range of distribution transformers supplied at 33 kV (which include the losses due to the leakage reactance).

Table 5.5: Reactive power consumption of distribution transformers with 20 kV primary windings.

Rated power KVA	Reactive power (kVAr) to be compensated			
	Oil immersed type		Cast resin type	
	No load	Full load	No load	Full load
50	1.5	2.9		
100	2.5	5.9	2.5	8.2
160	3.7	9.6	3.7	12.9
250	5.3	14.7	5.0	19.5
315	6.3	18.3	5.7	24.0
400	7.6	22.9	6.0	29.4
500	9.5	28.7	7.5	36.8
630	11.3	35.7	8.2	45.2
800	20	66.8	10.4	57.5
1000	24.0	82.6	12.0	71.0
1250	27.5	100.8	15.0	88.8
1600	32.0	125.9	19.2	113.9
2000	38.0	155.3	22.0	140.6
2500	45.0	191.5	30.0	178.2

Note: For a 630 kVA transformer the range of kVAr losses extends from 11.3 at no load. to 35.7 kVAr at full load. These values correspond closely to those given in the worked example above.

5.15 Compensation At The Terminals Of An Induction Motor

a) Connection of a Capacitor Bank and Protection Settings

Individual motor compensation is recommended where the motor power (kVA) is large with respect to the declared power of the installation.

General Precautions

The power factor of a motor is very low when they are lightly loaded or operating at no-load. The reactive current of the motor in such circumstances is small (since the kW consumption is also small). A number of unloaded motors together constitute a consumption of reactive power, which is generally detrimental to an installation, for reasons explained in preceding sections.

Two good general rules therefore, are that unloaded motors should be switched off, and motors should not be oversized (since they will then be lightly loaded).

Connection

It is always recommended to connect required capacitor to the terminals of the motor, considering the no-load kVAr requirement of the motor under consideration.

Special Motors

It is recommended that special motors (stepping: plugging; inching; reversing motors, etc.) should not be compensated.

Effect On Protection Settings

After applying compensation to a motor, the current to the motor-capacitor combination will be lower than before, assuming the same motor-driven load conditions. This is because a significant part of the reactive component of the motor current is being supplied from the capacitor as shown in Figure 5.17.

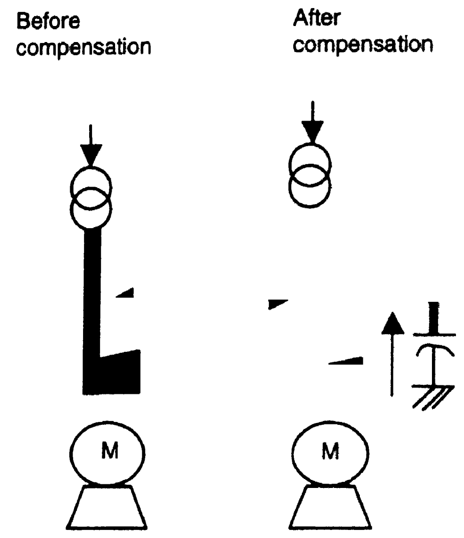


Figure 5.17: Before compensation the transformer supplies all the reactive power, after compensation the capacitor supplies a large part of the reactive power.

Where the over-current protection devices of the motor are located upstream of the motor-capacitor connection (and this will always be the case for terminal-connected capacitors) the over-current relay settings must be reduced in the ratio:

$$\frac{\cos\Phi \text{ before compensation}}{\cos\Phi \text{ after compensation}}$$

For motors compensated in accordance with the kVAr values indicated in Table 5.2, the above-mentioned ratio will have a value similar to that indicated for the corresponding motor speed in Table 5.6.

Table 5.6: Reduction factor for overcurrent protection after compensation.

Speed in R.P.M.	Reduction factor
750	0.88
1000	0.90
1500	0.91
3000	0.93

b) How Self-Excitation of an Induction Motor can be Avoided

When a capacitor bank is connected to the terminals of an induction motor it is important to check that the size of the bank is less than that at which self-excitation can occur.

When a motor is driving a high-inertia load, the motor will continue to rotate (unless deliberately braked) after the motor supply has been switched off.

The 'magnetic inertia' of the rotor circuit means that an emf will *be* generated in the stator windings for a Short period alter switching off, and would normally reduce to zero after 1 or 2 cycles, in the case of an uncompensated motor.

Compensation capacitors however, constitute a 3-phase 'wattless' load for this decaying emf, which causes capacitive currents to flow through the stator windings. These stator currents will produce a rotating magnetic field in the rotor, which acts exactly along the same axis and in the same direction as that of the decaying magnetic field.

The rotor flux consequently increases; the stator currents increase; and the voltage at the terminals of the motor increases; sometimes to dangerously-high levels. This phenomenon is known as self-excitation and is one reason why a.c. generators are not normally operated at leading power factors, i.e. there is a tendency to spontaneously (and uncontrollably) self-excite.

Notes:

1. The characteristics of a motor being driven, by the inertia of the load are not rigorously identical to its no-load characteristics. This assumption, however, is sufficiently accurately for practical purposes.
2. With the motor acting as a generator, the currents circulating are largely reactive. so that the braking (retarding) effect on the motor is mainly due only to the load represented by the cooling fan in the motor.
3. The (almost 90° lagging) current taken from the supply in normal circumstances by the unloaded motor, and the (almost 90° leading) current supplied to the capacitors by the motor acting as a generator, both have the same phase relationship to the terminal voltage. It is for this reason that the two characteristics may be superimposed the graph.

Example

A 75 kW, 3000 Rpm, 400 V, 3-phase motor may have a capacitor bank no larger than 16 kVAr according to Table 5.2. The table values are, in general, too small to adequately compensate the motor to the level of cosϕ normally required. Additional compensation can, however be applied to the system, for example an overall bank, installed for global compensation of a number of smaller appliances.

High-inertia motors and / or loads

In any installation where high-inertia motor-driven loads exist, the circuit breakers or contactors controlling such motors should, in the event of total loss of power supply be rapidly tripped.

If this precaution is not taken, then self-excitation to very high voltages is likely to occur, since all other banks of capacitors in the installation will effectively be in parallel with those of the high-inertia motors.

The protection scheme for these motors should therefore include an over-voltage-tripping relay, together with reverse-power checking contacts (the motor will feed power to the rest of the installation until the stored inertia energy is dissipated).

An under-voltage relay would not be suitable because the voltage is not only maintained but will increase immediately following the loss of power supply.

If the capacitor bank associated with a high-inertia motor is larger than that recommended in Table-5.2 there it should be separately controlled by a circuit breaker or contactor, which trips in unison with the main motor-controlling circuit breaker or contactor, as shown in Figure 5.18.

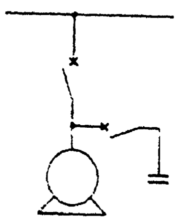


Figure 5.18: Connection of the capacitor bank to the motor.

Closing of the main contactor is commonly subject to the capacitor contactor being previously closed.

5.16 Example of an installation before and after power-factor correction

Installation before P F Correction

KVA = kW+kVAr

kVA

kW

kVAr

- KVAr are billed heavily above the declared level.
- Apparent power kVA is significantly greater than the kW demand.
- The corresponding excess current causes losses (kWh) which are billed.
- The installation must be over-dimensioned.

630 kVA

Characteristics of the installation
500 kW Cos ϕ = 0.75

- Transformer is overloaded
- The power demand is

$$S = \frac{P}{\cos\phi} = \frac{500}{0.75} = 665 \text{ kVA}$$

S = apparent power

- The current flowing into the installation downstream of the circuit breaker is :

$$I = \frac{P}{\sqrt{3}U\cos\phi} = 960 \text{ A}$$

- Losses in cables are calculated as a function of the current squared : $(960)^2$

$$P = I^2R$$

- Cos ϕ = 0.75
- Reactive energy is supplied through the transformer and via the installation wiring.
- The transformer, circuit-breaker, and cables must be over-dimensioned.

Cos ϕ = 0.75
workshop

Installation after P F correction

KVA = kW+kVAr

kVA

kW

- The consumption of kVArh is eliminated, or reduced, according to the cos ϕ required,
- The tariff penalties for reactive energy where applicable for the entire bill in some cases are eliminated ,
- The fixed charge based on kVA demand is adjusted to be close to the active power kW demand.

630 kVA

400 V

Characteristics of the installation
500 kW Cos ϕ = 0.75

- Transformer no longer overloaded
- The power demand is 539 kVA
- There is 14% spare-transformer capacity available.

- The current flowing into the installation through the circuit breaker is 778 A.

- The losses in the cables are

reduced to $\frac{(778)^2}{(960)^2}$ = 65% of the former value

there by economising in kWh consumed.

- Cos ϕ = 0.928
- Reactive energy is supplied by the capacitor bank

kVA

Capacitor bank rating is 250 kVAr in 5 automatically-controlled steps of 50 kVAr.

Cos ϕ = 0.928
workshop

Note : In fact, the cos ϕ of the workshop remains at 0.75 but cos ϕ for all the installation upstream of the capacitor bank to the transformer LV terminals is 0.928. As mentioned in sub-clause 6.2 the cos ϕ at the HV side of the transformer will be slightly lower. Due to the reactive power losses in the transformer.

5.17 Problems Arising from Power-System Harmonics

Capacitors are especially sensitive to harmonic components of the supply voltage due to the fact that capacitive reactance decreases as the frequency increases. In practice, this means that a relatively small percentage of harmonic voltage can cause a significant current to flow in the capacitor circuit.

The presence of harmonic components causes the (normally sinusoidal) waveform of voltage or current to be distorted: the greater the degree of distortion.

The presence of harmonics in the supply voltage results in abnormally high current levels through the capacitors. An allowance is made for this by designing for an r.m.s value of current equal to 1.3 times the nominal rated current.

All series elements, such as connections fuses, switches, etc. associated with the capacitors are similarly oversized, between 1.3 to 1.5 times nominal rating.

Capacitors are linear reactive devices, and consequently do not generate harmonics. The installation of capacitors in a power system (in which the impedances are predominantly inductive) can, however result in total or partial resonance occurring at one of the harmonic frequencies.

In this particular case, the elevated current will cause overheating of the capacitor, with degradation of the dielectric, which may result in its eventual failure.

Several solutions to these problems are available, which aim basically at reducing the distortion of the supply-voltage wave form, between the equipment causing the distortion, and the bank of capacitors in question. Shunt connected harmonic filter and / or harmonic suppression reactors generally accomplish this.

Harmonic distortion of the voltage wave frequently produces a 'peaky' wave-form in which the peak value of the normal sinusoidal wave is increased. This possibility together with other over-voltage conditions likely to occur when countering the effects of ' resonance', as described below are taken into account by increasing the insulation level above that of "standard' capacitors. In many instances these two counter measures are all that is necessary to achieve satisfactory operation.

5.18 Capacitor elements technology

The capacitors are dry-type units (i.e. are not impregnated by liquid dielectric) comprising metallized Polypropylene self-healing film in the form of a two-film roll.
They are protected by a high-quality system (over pressure disconnector used with an HRC fuse) which switches off the capacitor it an internal fault occurs.

The protection scheme operates as follows:

- short circuit through the dielectric will blow the fuse;
- current level greater than normal, but insufficient to blow the fuse sometimes occur, e.g. due to a microscopic flow in the dielectric film. Such 'faults' often re-seal due to local heating caused by the leakage current, i.e. the units are said to be 'self-healing'.

Capacitors are made of insulating material providing them with double insulation and avoiding the need for a ground connection.

Section 6: Quality of Power in A.C. System

6.1 General

The AC power system was conceived to deliver voltages and currents as close to sinusoidal as possible and maintain voltages and frequencies within specified close tolerances. "Ideal Power Quality" is a generic term used to indicate:

- Source from an infinite bus
- Purely sinusoidal wave form
- Constant voltage and frequency
- No interruptions

In practice, these ideal conditions are somewhat deviated; mostly being electromagnetic in nature. The simplest is the voltage drop experienced at the end of a feeder line due to line impedance. A lightning strike may temporarily elevate the voltage and current in the system or the introduction of a heavy load or operating a circuit breaker may disrupt a voltage condition momentarily. These are transient phenomenons.

6.2 Types of Power Disturbances

Transients are sudden, momentary changes in voltage or current that could be impulsive or oscillatory.

Impulsive Transients are sudden uni-directional (non-power frequency) changes in the steady state current or voltage or both, caused mostly by lightning or a tripping of the grid supply. They are of very high magnitude and sustain for a very short duration.

Oscillatory Transients are sudden bi-directional (non-power frequency) changes in voltage or current or both. These are generally the result of the switching on of a highly inductive load or capacitor bank.

Voltage sags or dips, swells and interruptions are short duration variations caused by line fault conditions, switching on of large loads, high starting currents and loose contacts in wiring. They last for a fraction of a cycle to a few cycles. Swells are less common.

Black outs, under voltage or over voltage conditions are variations occurring for a few minutes or more. It can be even consequent outage of supply.

Voltage imbalance of a three-phase system is mostly brought about by single-phase loads distributed unequally over the three phases and "blow off" of phase fuses in a capacitor bank.

DC offset occurs due to geometric disturbances and half-wave rectification. It increases saturation in transformers, reducing their life and leads to electrolytic erosion of grounding electrodes.

Noise in power system is caused by power electronic devices, arcing equipment, rectifiers, SMPS and control circuits using phase switching components. Improper grounding aggravates this problem. The noise is in the spectrum of 200 kHz.

Voltage fluctuations (flicker) when the load in the network changes, voltage tends to drop. If this is very frequent within the bandwidth of 90% to 110% of the voltage, it causes irritating flickers in lights and disturbs other loads. The types of loads, which are likely to cause fluctuations, are weldings, rolling mills, induction furnace and arc furnace.

Power frequency variation is a change in the system's fundamental frequency. The magnitude depends on the loading characteristics and dynamic response of the generator. In distribution systems, good grid networking reduces this problem to an extent. Lower frequencies are invariably due to overloading of the generator.

Filtering transients is not difficult. Isolation transformers can attenuate common mode transients and mitigate earth-neutral related problems. LC line filters can be used effectively to reduce the magnitude of transverse mode noise and, to a lesser extent, mode noise. Devices like MOVs and gas arrests absorb high voltage spikes and transients. The other types of power disturbances require different types of correction, some of which are in vogue.

However, the term **Power Quality** used in the present context excludes the classical phenomena of the type mentioned above and focus on the problem of **Harmonics (non Sinusoidal Waveforms).**

Waveform distortion refers to all deviations of current and voltage from an ideal sinusoidal waveform of power frequency.

6.3 Harmonics in Power Systems

The extensive use of power electronic devices has increased harmonic "pollution". Since there is no viable alternative for these non-linear devices in electrical engineering, the subject of supply harmonics presently has broad interest. According to the Electric Power Research Institute (EPRI), presently "35-40% of all electric power flows through electronic devices. This is supposed to increase to 60% by the year 2000".

Supply of harmonics is also caused by transformers, motors, and rectifiers; they have been detected as early as the 1920s and 30s. A system can function adequately, however, in the presence of limited amounts of harmonics, and in the past amounts injected into systems were generally considered insignificant. Isolated problems caused by large industrial users were handled by locally reducing the harmonics to a more tolerable level. A method such as phase multiplication could be used to reduce harmonics at a site with a balanced load. Today, however, increased industrial and consumer dependence on equipment with non-linear components is aggravating the situation. We are, in fact, not only increasing the amounts of harmonics put into systems, but we are using equipment that is more susceptible to damage by the harmonics.

A harmonic is defined as a sinusoidal component of a periodic wave or quantity, which has a frequency that is an integral multiple of the fundamental frequency. The presence of harmonics causes the waveform (normally sinusoidal) of voltage and current to be distorted. The greater the harmonic current, the greater the degree of distortion (see figure 6.1).

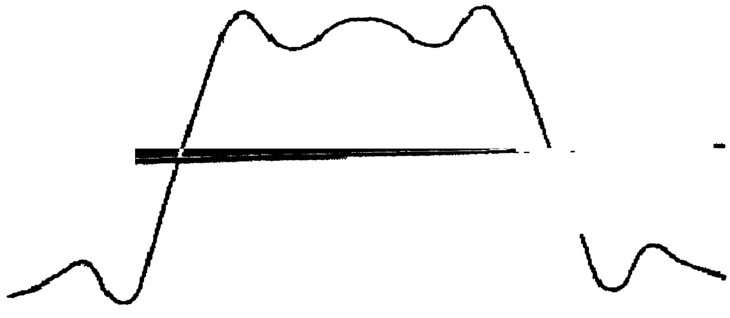


Figure 6.1: Distorted wave

Harmonic is caused by the non-linear magnetising impedance of transformers, reactors, fluorescent lamp ballasts etc. They are a result of loads that require currents other than sinusoid. Typically some sources of harmonics are:

- Arc furnaces and other arc discharging devices
- Resistance welders.
- Magnetic cores that require third harmonic current
- Synchronous machines
- Adjustable speed drives
- Solid state switches - that modulate the current
- Switched mode power supplies
- Computer and peripherals
- High voltage DC transmission stations
- Photo-voltaic inverters

Rectifiers are used in industries for d.c drives and for inverter-fed a.c. drives, which are required for variable speed application. These are sources of phase-controlled harmonics (Even harmonics are caused by three-phase half controlled bridge, 5^{th} and 7^{th} harmonics are caused by fully controlled 3-phase bridge and 11^{th} and 13^{th} harmonics are produced 12 pulse converter).

In a balanced 3 phase system, the triplen harmonics (3^{rd}, 6^{th}, 9^{th} etc.) have the same instantaneous magnitude in each phase. When triplen harmonics appear in a low voltage system, they can overload the neutral conductor and also circulate in delta winding in distribution transformer. Normally harmonics on 3 phase symmetrical power systems are odd numbered: 3^{rd}, 5^{th}, 7^{th}, 9^{th}, etc. and the magnitude decreases as the order of the harmonic increases.

Typically the 4^{th}, 7^{th}, 10^{th}, 13^{th} have some phase sequence (positive sequence), while 2^{nd}, 5^{th}, 8^{th}, 11^{th}, etc. harmonics have the reverse phase sequence (negative sequence).

6.4 Effects of Harmonics on Power System

Capacitors are specially sensitive to harmonic components of the supply voltage due to the fact that capacitive reactance decreases as the frequency increases.

If the natural frequency of the capacitor bank/power system reactance combination is close to a particular harmonic, then it cause partial resonance in

capacitor banks resulting in increased voltage and current at the harmonic frequency concerned. In this case elevated current will cause overheating of capacitor, with degradation of di-electric resulting in eventual failure.

The large use of shunt capacitors to improve power system power factor and voltage, has significant influence on harmonic levels. Capacitors do not generate harmonics, but provide a circuit for possible resonant conditions. The resonant frequency of a low voltage system with capacitor bank can be found from formula.

$$F_r = 50\sqrt{\frac{kVA_{sc}}{kVA_{rc}}}$$

Where,

kVA_{sc} - at short circuit level

kVA_{rc} - capacitor bank

Following effects can normally be observed in presence of harmonics in power system.

- Increased line losses
- Additional losses due to heating.
- Reduced efficiency and increased losses in rotating m/c.
- Increased losses and stress on insulation of transformers.
- Overstressing of capacitor and cable insulation failure.
- Control and monitoring equipment register improperly, relays mal-operate.
- Voltage distortion, and
- Peak waveform has been known to travel through distribution system and create problems at industrial sites without their own source or harmonics.

a) Conductor loss

The high frequency currents of the harmonics tend to flow towards the skin of the conductor. The value of resistance itself increases as only a portion of the conductor is effectively used. This is known as "skin" effect. The resultant heating effect is felt on the winding of the transformer, motors and all wound components. In effect, the heating effect will be felt in machines, transformers, transmission lines and loads wherever the harmonics flow.

b) Iron loss

Iron loss is dependent on the magnetisation-demagnetisation cycle. It is obvious that the core of the transformer and motor go through this cycle several times more than the usual 50 Hz due to the presence of harmonics. The increase in iron loss takes place in all ferromagnetic equipment.

c) Di-electric loss

The dielectric loss or the 'tanδ' component is also frequency dependent, thus increasing in the presence of harmonics. The dielectric loss takes place in capacitors normally provided for power factor correction.

d) Control and Metering

Metering and instrumentation are affected by harmonic components, particularly if resonant conditions exist that result in high harmonic voltages and currents. Induction disk devices such as watt-hour meters, normally register only fundamental current that is in phase with the fundamental voltage. Harmonic voltage will also register on the meter. Since most harmonic voltage is out of phase with harmonic current, harmonic power is small. Studies have shown that positive and negative errors are possible with harmonic distortion, depending upon the type of meter under consideration and the harmonics involved. In general, the distortion factor must be severe (> 20%) before significant errors can be detected.

6.5 Effect on Equipment

a. Motors and generators

- Higher audible noise
- Cogging (the refusal to start smoothly) and crawling (very high slip) phenomena are enhanced, in induction motors.
- Mechanical oscillations in a turbine-generator or a motor-load system.
- Reduced efficiency

b. Transformers

- Increased audible noise.
- Additional copper losses and stray-flux losses.
- Increased iron losses, if voltage harmonic is present

c. **Power cables**

- Increased voltage stress and corona, which may lead to dielectric failure.
- Additional heating over that expected for the rms. value of the waveform.

d. **Capacitors**

- Increased di-electric stress and heating within the capacitor.
- Loss of life.

e. **Communication links**

- Unwanted noise
- Data loss

Even remote harmonic sources from other industries may result in similar problems. In general, the effect of harmonics is a reduction in the efficiency and life of the machine.

6.6 Industrial Standards

Harmonic standards can be broadly classified into two types. (i) System standard. (ii) Equipment standards.

System standards are related between utility system and the consumers load, are more concern to utilities at present. The equipment standards further divided into harmonic emission, emission standards and susceptibility standards.

System standards

IEEE 519-1992	-	Low, medium and high voltage system
IEC-1000	-	Low voltage systems
IEC-77B	-	Medium voltage system

Equipment standards

IEEE 446-1987	-	Disturbance susceptible standards
IEC-555	-	Harmonic emission standards.

The harmonic current limits and voltage distortion is listed in Table 6.1 and 6.2.

The current distortion limits are dependent upon the size of the customer's load relative to the available short circuit capacity of the utility . In this way, customers whose loads have more effect on the utility system and neighbouring customers are bound by tighter limits.

Two very important points must be made in reference to the above limitations.

- The customer is responsible for maintaining current distortion to within acceptable levels, while the utility is responsible for limiting voltage distortion.
- The limits are only applicable at the Point of Common Coupling (PCC) between the utility and the customer.

The PCC, while not explicitly defined, is usually regarded as the point at which utility equipment ends and the customer's equipment begins, or the metering point. Therefore, the above limits cannot be meaningfully applied to, say, distribution panels or individual equipment within a plant - the entire plant must be considered while complying with these limits.

a) Harmonic Analysis

Harmonic analysis can be carried out on the network with the aid of a harmonic analysis. Figure 6.2 illustrates one period of a distorted wave that has been resolved into its fundamental and two in-phase harmonic components (the third and fifth). The decomposition of a periodic wave in this manner is referred to as Fourier analysis.

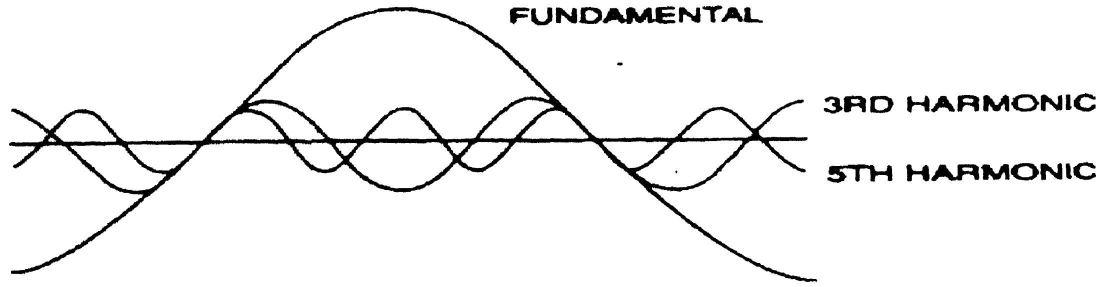


Figure 6.2: Illustration of distorted wave as fundamental plus third and fifth harmonic components

The waveform is sampled and the analysis be made to tune out various frequencies. The 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics can cause resonance in capacitor banks and are source of noise in communication circuits. The third harmonics is the most prevalent and is generally of the highest magnitude.

Delta/Star connected transformers are excellent natural filters for 3rd harmonics. Increasing the short circuit level of the system by using lines and/or transformers in parallel, reduce the effect of harmonics.

Total Harmonic distortion (THD)

Two of the most commonly used yardstick to indicate harmonic content :

- THD
- Crest Factor

"THD" is computed as :

$$THD_V = \sqrt{\sum_{n=z}^{n=n_{max}} \left(\frac{V_n}{V_1}\right)^2} \times 100\%$$

where,

V_1 = fundamental

V_n = n^{th} harmonic.

IS:325-1978 limits total harmonic distortion in voltage is upto 5%

"Crest factor" is the ratio of the voltage or current peak to the peak of a purely sinusoidal waveform of the same RMS value. When the waveform distorts, it ceases to be a sine wave of a single frequency. It becomes spiky, rounded or squarish in shape and the relationship between the rms value and peak voltage does not hold. Crest factor is computed as follows.

$$\text{Current crest factor} = \frac{I_{peak}}{\sqrt{2 \times I_{rms}}}$$

Flow of Harmonic current

All the non-linear loads draw non sinusoidal currents, which cause distortion in the voltage wave form. Individual harmonic frequency magnitudes can be represented as a percentage of the fundamental component. The crest factor measures one type of distortion. The effect of harmonics in different situations can vary and hence different methods of characteristics of them are required. The fundamental wave of the current is alone responsible for the transport of energy to the load. The

harmonic current does not contribute to the transport of energy and they represent an undesirable phenomenon as they reduce the power factor.

The fundamental wave frequency content g is the ratio of the fundamental frequency current I, to the total AC line current I_L

$$g = \sqrt{\frac{\sum_{n=2} In^2}{I_L}}$$

Table 6.1: Harmonic current Limits as per IEEE standard 519

Maximum Harmonic Current Distortion in % of I_L						
Individual Harmonic Order (Odd Harmonics)						
Isc/I load	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.S	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonic limits above.						
Current distortions that result in a direct current offset, e.g., half wave converters are not allowed.						
* All power generation equipment is limited to these values of current distortion, regardless of actual Isc/I_L.						
Where, Isc = Maximum short circuit current at Pcc. And I_L = Maximum Demand Load Current (fundamental frequency component) at PCC; TDD = Total Demand Distortion.						

Table 6.2: Maximum Voltage Distortion (SEB /Utility) as per IEEE Standard 519

Bus voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161 kV and above	1.0	1.5
Note : High voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.		

6.7 Harmonic Mitigation

Once the system is studied and harmonic analysis is completed, there are several options available to solve or alleviate problems introduced by harmonics, including derating, passive filters, and harmonic filtering or current compensation methods which use active devices.

As an alternative to reducing harmonics, it has been suggested that some of their potentially damaging effects be merely avoided by, for example, derating transformers and oversizing neutrals. This could be an adequate solution in some cases, but again, since system changes can cause changes in the amounts of harmonics in the system, the exact amount of derating or oversizing necessary could be difficult to predict. Also, this option does not prevent harmonics from entering the supply system.

Passive filters can prevent harmonics from entering a supply system, and are also useful in increasing power factor. However, these filters are designed to filter specific harmonic components; they are not adaptable to successfully filter varying harmonics.

Further, passive filters must be carefully sized. Undesirably large bus voltages can result from using an oversized filter, and an undersized filter can become overloaded. Finally, other complications, such as those related to resonance, are possible. Inter-action between the capacitance in passive filters and system impedance can, in fact, result in a system resonance condition. This resonance condition can persist even with the filter tuned slightly below the system resonant frequency. Also, changes in the distribution system can cause the resonant point itself to change. All of these points can be drawbacks to the passive filter option.

The shortcomings of the options of derating and passive filters points to the fact

that these techniques may not be optimal methods of dealing with a harmonic problem. The use of active filters or harmonic current compensation circuitry to eliminate harmonics before they enter a supply system is still generally thought to be costly and impractical. But technological improvements and considerable research are combining to make this approach feasible.

Taking the concept of harmonics elimination at the source even a step further, many are of the opinion that perhaps the best solution would be to solve the problem even more directly, by incorporating harmonics compensation circuitry into the harmonics producing equipment itself. This might be considered a step toward the ideal equipment that does not produce harmonics. New converter system designs will feature power quality improvement. Still, others do not believe that fitting individual units can be considered to be an economical approach.

6.8 Harmonic Filters

Once the orders of the harmonics are known, suitable harmonic filters can be designed to suppress them. It is unlikely that the waveform has only one type of harmonic. For example, it is likely that if the waveform under analysis is rich in the 3rd harmonic, the 5th and 7th harmonics will also be present. Filters have to be designed for each of the frequencies, taking into account their magnitude. The size of the filter is dependent on the harmonic content. Higher order filters are always smaller than filters of the lower order harmonics.

Type of Filters

Filters are necessarily LC circuits of various combinations. At the tuned harmonic frequency, the reactance of the capacitor and inductor of the filter balance each other and the impedance of the filter is purely resistive at that frequency. Therefore, at the tuned frequency, the filter provides the lowest impedance path for the voltage and current to ground. This phenomenon enables the design of filters for specific frequencies. At other frequencies, the filter becomes capacitive or inductive depending on the frequency. Hence, the filter generates reactive power at the nominal line voltage. The filter should, therefore, be brought into the circuit only when the harmonic generating equipment is in operation.

Filters can be series resonant or parallel resonant and can be band pass, double band pass or high pass filters as shown in Figure 6.3.

Band pass filter (figure 6.3a) is a series combination of capacitors and reactor. To make the band wider, a series resistor is added as shown.

The impedance of a **double band pass filter** (figure 6.3b) is low at two tuned frequencies and impedance characteristics are similar to the net characteristics of two single band pass filters tuned to the same frequency. This is an economical way of combining filters for certain applications.

A high pass filter (figure 6.3c) consists of a capacitor and a resistor and provides a low impedance path for higher order harmonics. It is immune to the tuning effect of temperature and source frequency variations. The losses due to these filters are high, especially if it is used to filter lower order harmonics.

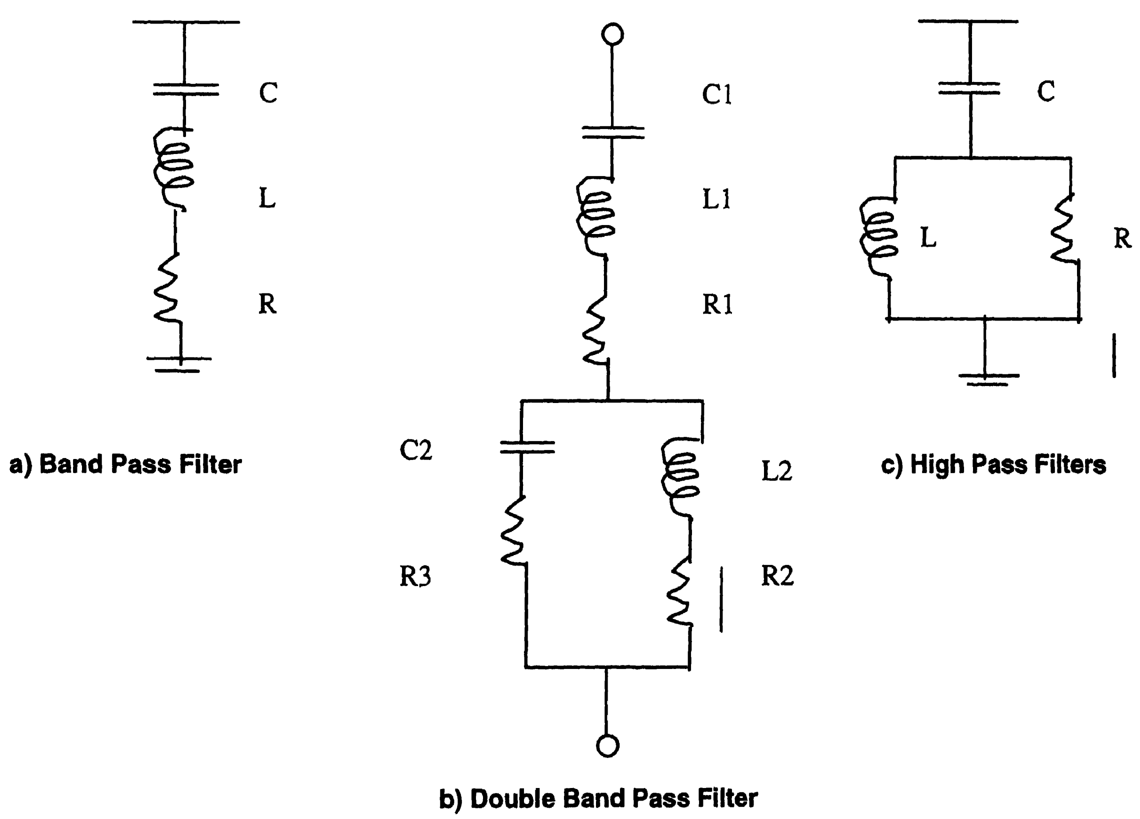


Figure 6.3: Different Types of Filters used for Harmonic Mitigation

6.9 Harmonics and Resonance

One of the main problems associated with harmonics is resonance. This reflects in the filter design also. Whenever a capacitive impedance is located near a harmonic source, there exists a potential for a voltage resonance, which must be taken care of by design. A resistance in series with the filter is introduced to make it broad band, so that resonance does not set in. It is a good practice to analyse the harmonic again after the introduction of filters.

Anyway the astounding improvements in power electronic technology of the past 10 years, including MOS-controlled thyristors and microprocessor-based control circuitry, will ultimately permit simpler, more efficient and reliable, and less costly active filtering and current compensation system designs. Therefore, the allure of the power electronics harmonics solution, whether unit incorporated or system-based, will only increase.

Section 7: Electricity Supply Equipment Efficiency

Around 10 to 15 percent of the power is usually lost in the transmission of power from the generating station to the consumers. The balance is drawn by utilisation devices. The problem should mainly be tackled by the process and power supply engineers of every factory, through judicious use of power in the process and auxiliary plant.

7.1 Losses

All electrical equipment has some type of loss associated with its use. There are five types of losses that should be considered to determine optimum operating point for an equipment:

a. Magnetic losses (no-load) are associated with motors, transformers, reactors, regulators, etc. These losses are usually a function of voltage square and consist of hysteresis and eddy current.

b. Load (Copper) losses are associated with the flow of current which are a function of the square of the current from the equation $P = I^2R$.

c. Motion losses as the equipment operates, include friction loss bearings, wind, and system restrictions.

d. Mechanical losses are reflected in the electric circuit power requirements. These losses include inefficiencies associated with transmissions, eddy current clutches, and speed-control devices.

e. A combination of factors will cause additional or unnecessary losses, if an equipment is operated outside its design limits.

The reduction of losses in the components of the power supply system is very relevant, as even one percent of the power saved results in enormous blocks of power available for utilisation elsewhere. Operating the equipment far below rated capacity results in a waste of capital investment and causes an increase in the no-load portion of the losses, thus lowering the power factor. The key to energy engineering is to match the device to the load and the power supplied to the device.

a) Percentage Loss at Rated Load

Following table indicate possible loss as percentage of full load for few electrical equipment

Sl. No.	Equipment	% Full Load (max load)
A C Motors		
i.	750 Watts - 7.5 kW	14 - 35
	7.5 kW - 150 kW	6 - 12
	150 kW - 1000 kW	4 - 7
	Above 1000 kW	2.3 - 4.5
ii.	Transformers	0.4 - 1.9
iii.	Cables	1 - 4
iv.	Switch gear	
	L.T.	0.13 - 0.34
	Medium voltage up to 11 kV	0.005 - 0.02

7.2 Evaluation of Cost Losses

The annual cost of supplying losses can be broken down into two major parts:

a. Energy component or production cost to generate kWh losses $= 8760\ F_L\ E$.

b. Demand component, or annual costs associated with system investment required to supply the peak kW of loss $= F_S P$.

Where F_L = Loss factor of load
B = Cost of energy, Rs/kWh
F_s = Responsibility factor
P = Annual cost of system capacity, Rs/kW-year
E = Energy Cost

Annual cost of losses can be combined into one value, in terms of either rupees per kilowatt - hours or rupee per kilowatt year of peak loss with the following formulas.

$$\text{Cost of losses Rs/kWh} = \frac{F_S P}{8760\ F_L} + B$$

$$\text{Capitalised cost of losses, kW-year} = F_S P + 8760\ F_L B$$

Expressing losses in terms of rupees per kilowatt is usually called `capitalised' cost of losses, and it shows directly the amount of money that could be economically spent to save 1 kW of loss. However, the expression of cost of losses in rupees per kilowatt-hour is usually a more convenient form to use in most engineering studies.

The cost of losses depends on the point of occurrence in the system. The further out the losses occur, the greater is the value of the loss. One kilowatt of loss saved on the secondary system is worth more than 1 kW loss at generation because of the cumulative effect of increment of losses, as they pass through various elements of the system.

In calculating loss, present day or future cost of system investment should be used. The incremental investment, in rupees required to supply an incremental load in kilowatts is of primary interest.

7.3 Loss Factor

'Loss factor' is usually defined as the ratio of the average power loss, over a designated period of time, to the maximum loss occurring in that period. The term can refer to any part or whole of the electric system. It is also known as the **`load factor of the losses'**.

If the peak conductor losses of a cable or transformer have to be calculated, it is necessary to know the loss factor or percent equivalent hours to calculate the actual losses over a period of time.

A corollary to `loss factor' is the term `equivalent hours'. This is defined as the number of hours per day, week, month, or year or peak load necessary to give the same total kilowatt hours of loss as that produced by the actual variable load over the selected period of time. The period of time for distribution studies is usually one year, and it is obvious that `percent equivalent hours' has the same meaning as the term `percent loss factor'.

The definitions of `loss factor' and `load factor ' are similar. There is a relationship between the two factors, dependent upon the shape of the load curve. Since resistance losses vary as the square of the load, the value of loss factor can vary between the extreme limits of load factor and load factor squared. The relationship between load factor and loss factor at the distribution transformer can be expressed by the empirical formula:

$$\text{Loss factor} = K_1 \ \text{load factor} + K_2 \ (\text{load factor})^2$$

Where,

$$\left.\begin{array}{l} k1 - 0.15 \text{ to } 0.3; \\ k2 - 0.7 \text{ to } 0.85 \end{array}\right\} \text{depending on type of load}$$

However, if the shape of the load curve is known or can be reasonably estimated, the loss factor should be calculated directly and not determined by the empirical formula.

7.4 Efficiency

In any energy evaluation, the efficiency of a device is given by.

$$\%\ \text{Energy Efficiency} = \frac{\text{kWh Out (Operating Cycle)}}{\text{kWh In (Operating Cycle)}} \times 100$$

A nameplate or full load efficiency rating is given to almost all equipment.

7.5 Capacitors

Capacitors can be significant energy savers, if they are properly applied A capacitor bank is also a load albeit with very low loss (0.2-0.4 W/kVAr). So it should be disconnected when VAr support is not required If a fuse blows on a large capacitor, an unbalanced voltage occurs along with resultant increases in system and motor losses. Therefore, the fuse integrity of capacitor banks should be closely monitored. A high harmonic content in the power supply has been known to cause either capacitor failure or unplanned operation of protective devices. Hence use of latest semi conductor devices with appropriate technology can prove beneficiary in the long run.

7.6 Transformers

a. Losses

The transformers can be either distribution type (upto 630 kVA) or power type (above 500 kVA). Usually each sub-station has its own step down transformer to supply voltages less than 1000 Volts.

The power transformers have been standardised in various capacities. The selection depends upon the maximum load requirements in the area. Most of the transformers are provided with off-circuit taps. To compensate for small variation in primary supply voltage. On-load tap changing devices could be provided with higher capacity transformers on demand by the utility.

While designing the size of a new transformer, it should be assumed that operation is at 60-70 % of its full load. If the average load is 80 % or more of the rated power, a bigger or second transformer should be considered, because the load losses can become significant in the total losses.

The total transformer losses P_t during operation are :

$$Pt = P_0 + \left(\frac{P_s}{P_N}\right)^2 P_{sc}$$

Where,

P_t = Total power losses in kW

P_o = No load loss in kW

P_{sc} = Load loss in kW

P_s = Actual load of transformer in kVA

P_N = Rated power of transformer in kVA

Transformers are static and therefore efficient devices. Load losses (P_{sc}) are a function of the square of the ratio of load kVA to nameplate kVA. No-load (P_o) losses are a function of voltage squared.

Dry-type transformers are now-a-days used in industries. The losses of these units are significant. They should be switched off when not in use, whenever possible. In case of fluctuating loading conditions, over a

period of 24 hours, the all day efficiency could be lower. Any change in loading pattern, due to flexibility of operation in a group of transformers will improve the all day efficiency.

b. Reduction of power losses by deployment of higher voltages

Significant power can be saved by the installation of a transformer supplying 110, 66, 33, 11 and 6 kV next to the associated utilisation devices, and by pruning the length of low voltage circuits (0.4 kV). However, higher the voltage of the supply lines, the more expensive the apparatus, cables insulation and overhead line support. Hence judicious combination of different level of distribution voltage is adopted.

c. Reduction in Losses

While the iron losses of transformers cannot be reduced, the load losses in transformers reduce with demand control and with improvement of load power factor (for same kW load). This is due to reduction of peak kVA load carried by these units. The percentage reduction in peak demand (kVA) with improvement of power factor and the corresponding percentage reduction in peak losses (kW) are given below. Actual reduction in the annual energy consumption can be evaluated by the average loss reduction:

$$\text{Average loss reduction} = \text{Peak loss reduction} \times (K_1\, LF + K_2\, (LF)^2)$$

Where,

$$\left.\begin{array}{l} k_1 = 0.15 \text{ to } 0.3 \\ k_2 = 0.7 \text{ to } 0.85 \end{array}\right\} \text{depending on type of load}$$

For example, improvement of power factor from 0.85 to 0.96 gives 11.5 % reduction in peak kVA and 21.6 % reduction in peak losses, which correspond to 14.5% reduction in average losses for a load factor (LF) of 0.8.

Following table gives the % reduction in peak demand and losses by improving the load p.f.

Table 7.1: Percentage Reduction in Peak Demand

New PF / Old PF	0.92	0.94	0.96	0.98	1.0
0.70	23.91	23.53	27.08	28.57	30.0
0.75	18.48	20.21	21.87	23.47	25.0
0.80	13.04	14.89	16.67	18.37	20.0
0.85	7.61	9.57	11.46	13.57	15.0
0.90	2.17	4.26	6.25	8.16	10.0

Table 7.2: Percentage Reduction in Peak Losses

New PF / Old PF	0.92	0.94	0.96	0.98	1.0
0.70	42.11	44.55	46.83	48.98	51.00
0.75	33.54	36.34	38.96	41.43	43.75
0.80	24.39	27.57	30.56	33.36	36.00
0.85	14.64	18.23	21.60	24.77	27.75
0.90	4.30	8.33	12.11	15.67	19.00

The following points can be helpful for energy savings in transformers.

- Transformers can be switched off on holidays or periods of no load. Many industries do this regularly. When switching on, insulation levels, temperatures etc., can be checked, especially during the monsoon.
- Unlike motors, fans and similar equipment, transformer efficiencies are maximum at 50 % to 70 % load. When transformer capacities are available, it may be advantageous to run a number of transformers : if 1000 kW load is taken on 1000 kVA transformer, efficiency is 98.64 %. But, if two 1000 kVA transformers are available, load on each will be 500 kW and may account for increased savings in loss/money, if both are energised simultaneously . The efficiency will be 99.08 % , with a gain of 0.44 %.
- If transformers are oversized to a certain extent, there is not much loss. If 500 kVA load is carried on 1000 kVA transformer, there is some gain. This, however, does not justify the selection of very large transformers.
- Improvement of p.f. on L.T. side would reduce current and, thus, losses.

7.7 Cables

a. Losses

In-plant cable losses are in the range of 1% to 4 %. The following table gives cable loss for various sizes of aluminium conductors.

Table 7.3: I^2R Losses per Phase (in Watts) of Various Sizes (in mm^2) of Aluminium Cables of 10 m Length in a 3 Phase System

Size (mm^2) Amps	25	35	50	70	95	120	150	185	240	300
15	2.7	1.95	1.4	0.99	-	-	-	-	-	-
30	10.8	7.8	5.8	4.0	-	-	-	-	-	-
45	24.8	17.6	13.0	9.0	6.5	-	-	-	-	-
60	43.2	31.2	23.1	15.9	11.5	9.1	7.4	5.9	-	-
75	-	48.8	36.1	24.9	18.0	14.2	11.6	9.2	7.0	5.6
90	-	-	51.9	35.9	25.9	20.5	16.7	13.3	10.1	8.1
105	-	-	70.7	48.8	35.3	27.9	22.7	18.1	13.8	11.0
120	-	-	-	63.8	46.1	36.4	29.7	23.6	18.0	14.4
135	-	-	-	80.7	58.3	46.1	37.5	29.9	22.8	18.2
150	-	-	-	-	70.0	56.9	46.4	36 9	28.1	22.5
165	-	-	-	-	87.1	68.9	56.1	44.6	34.0	27.2
180	-	-	-	-	-	82.0	66.7	53.1	40.5	32 4
195	-	-	-	-	-	-	78.3	62.4	47.5	38 0
210	-	-	-	-	-	-	90.8	72.3	55.1	44.1
225	-	-	-	-	-	-	-	83.0	63.3	50.0
240	-	-	-	-	-	-	-	94.5	72.0	57.6
255	-	-	-	-	-	-	-	-	81.3	65.0
270	-	-	-	-	-	-	-	-	91.1	72.9
285	-	-	-	-	-	-	-	-	101.1	81.2
300	-	-	-	-	-	-	-	-	112 5	90.0
315	-	-	-	-	-	-	-	-	-	99.2
330	-	-	-	-	-	-	-	-	-	108.9
345	-	-	-	-	-	-	-	-	-	119.0

b. Loss Reduction

Power losses in lines depend upon the resistance of the lines and the current carried. The resistance of lines may be considered constant. Then it follows that the only way to reduce the loss of power is to reduce the current. The current may be reduced by using as many reserve lines as possible. Dual lines should be connected in parallel for a more economical operation.

Cable laying should be done strictly in accordance with carefully and systematically planned schedule. Drawing of this should be available at site and should be preserved at sub-stations. All cable ends should be suitably labeled to facilitate easy identification. In all control cables adequate number of spare cores should be included. For cables, use IS:1255-1958, IS:962-1965 and IS:3043-1966 standards.

c. Oversizing of Cables

As energy prices are rising faster than material prices, it may be worthwhile to invest in larger sizes of cables than required by thermal capacities. This is helpful for future expansion also.

In some cases of high loss, the cost of losses will justify installation of wiring that exceeds the current rating of the circuit. In many cases, there may not be much change in the cost of the feeder, over current device, conduit, pull boxes and the receiving panel. In such cases, over-sizing is justified. However, when over-sizing costs are significant, the ideal must be carefully considered to check if the cost of the losses can actually offset the cost of over-sizing. Installation of capacitors at distribution boards reduces cable currents and losses. Feeders can be switched off when not required.

7.8 Busbars

To supply large capacity loads such as electric furnaces etc., multi-bar bus-ways are used. In the bus arrangements of figure 7.1(a), the power losses in the bus-way are higher than in the arrangement of figure 7.1 (b). This is due to the proximity effect, which brings about an abrupt rise in the inductive reactance of the buses, and a comparable rise in the reactive component of the current, thus

entailing an increase in the total current and power loss. When buses are arranged as in Figure 7.1(b), their magnetic fields cancel each other and increase in reactive current is negligible. Hence loss of power is halved, compared to Figure 7.1(a).

7.1 (a) 7.1 (b)

Figure 7.1: Arrangement of Busbars

Section 8: Captive Power Generation

8.1 Introduction

Various forms of energy like heat, motive power, refrigeration, etc., is utilised in industrial activity. Application of electrical energy is common for most of these industrialised applications from the viewpoint of ease of transmission, distribution and flexibility, efficiency conversion, process adaptation and integration through excellent logic control techniques. Many of the continuous process industries like sugar, paper, ore refineries, chemical etc require large quantities of steam for process requirements in addition to electrical energy. Thus, 'TOTAL ENERGY' concept is getting increasing acceptance in these industries towards use of various forms of energy requirement.

With the rampant power shortage, poor power quality, disturbances, increased energy costs, as seen in the present SEB grid power distribution, industries are put to tremendous difficulties resulting in production losses, etc., This has lead to the need for captive power generation.

Need For Captive Generation

Industries have several advantages in going for Captive Generating sets. Captive power generation offers the following advantages:

1. Continuous availability of power, free from utility power breakdown and grid disturbances, etc., leading to better productivity, less interruptions in process restart etc.,
2. Good power system control obtained when operated in parallel with the utility supply system
3. Possibility of heat and electrical energy generation (Cogeneration) resulting in energy conservation and reduced energy cost,
4. Excess electrical energy generation can be supplied to the utility grid and earning income/ wheeling charges.

8.2 Selection of Captive Generation Equipment

Based on the energy requirements, availability of fuels, availability and reliability of grid power at the plant location, industries should take up a detailed and careful study to decide the type of generating equipment, its rating and other specifications. Different modes of operating the Captive generation units are defined based on IEEE standard 446.

Following modes of operation may be considered:

1. Standby Power supply Mode (Emergency Power Supply):

   Captive power generation set utilised in this mode shall meet the plant part load or total load requirement during the failure of utility power supply (Grid supply system).

2. Peak Loading Mode (Peak Lopping/Peak Shaving):

   The captive power generation units are chosen to come into operation during peak load periods to supplement the utility supply (Grid supply) to limit the peak demand drawn from utility and thereby saving the electricity cost paid towards maximum peak demand.

3. Base Load Mode (Primary Supply Mode):

   This mode of operation is required in locations where there is no utility power supply or the utility supply is highly unreliable with frequent outages. A part or whole of the plant load is supplied on a continuous basis in this mode of operation. This mode of operation can also be termed as Total Energy mode. Industries where the requirement of heat and cooling water supply, apart from electricity opt for this mode of operation in the initial design stages.

8.3 Mode of Generation

Mode of captive generation can be classified into one of the following:

a. Simple Mode;
b. Cogeneration Mode

a) Simple Mode

This mode of generation is usually by employing the diesel generating sets/ steam turbo sets or gas turbine sets of adequate capacity catering to supply requirement of a section of load or the total load operating in standby or base load mode. Sometimes a number of these units are used either in single mode supplying individual load sections or the units are operated in parallel to cater to entire plant load.

b) Cogeneration Mode

Co-generation is the combined production of electrical or mechanical energy and heat. The heat can be in the form of hot gases, hot liquids, or process steam.

The combined generation of work (electrical or mechanical) and process heat provides a better overall utilisation of the fuel used in a plant. For example, a plant that simultaneously needs electricity and low-temperature heat could be served in a variety of ways:

1. Buy or make electricity and use a portion to meet thermal requirement through resistance heating.
2. Buy or make electricity and use oil, gas, wood or coal to meet thermal requirement
3. Make electricity and use the rejected heat to meet thermal requirement.

The fuel consumption of option 3 is the least. If the energy for heat were the same for all three options, the incremental fuel for electricity in option 3 is 50 percent less than what would be required at a central utility plant to generate the same amount of electricity.

For option 3, the electricity and heat needs of the plant must match, which is unfortunately not the case with many industries. They cannot therefore, combine their production.

Co-generation includes topping units where primary energy is used to produce electricity and rejected heat is used to satisfy the needs of a relatively low-temperature thermal process and bottoming units where energy is used first to satisfy the thermal demands of a high-temperature process and rejected heat is then used to produce power. In near term, topping units offer more opportunity for energy savings, because of the ready availability of appropriate technologies and low-temperature processes account for majority of thermal demands.

Combined Cycle Mode

This is an extended form of cogeneration mode in which a Gas turbine generating set meets a part of electrical energy generation. The exhaust gas is utilised in the heat recovery steam generator to generate high-

pressure steam. The high-pressure steam is used to generate additional electrical energy through a steam turbo set. The exhaust steam of the steam turbo set is subsequently used for the plant process requirement. Combined cycle mode offers a better efficiency of energy utilisation as compared to simple mode.

8.4 Technologies Currently Available for Cogeneration

a) Extraction Steam Turbine-Generator

High pressure, high temperature steam is raised in a boiler, fed to a turbo-generator, and extracted from the turbine at temperature and pressure suitable for process thermal needs. The major advantage of this system is that it can use various fuels, including coal and industrial wastes. To meet process-steam pressures electricity generation of 150-220 kWh could be achieved per million kCal of energy delivered to the process.

b) Combustion Turbine System with Waste-Heat Boiler

This system uses the high-temperature (425°C) turbine exhaust to generate steam in a waste-heat boiler. The hot exhaust may also be used directly in some industrial processes. In comparison with the steam-turbine method, the power generated per unit of process thermal energy is higher. The chief disadvantage is the fuel inflexibility of current turbine technology, limited to natural gas or petroleum distillates. More utilisation of gas turbines for co-generation would cause a shift from coal and nuclear fuels used in central stations to gas and distillate. Development work is progressing on the use of residual oils and coal derived fuels, but reliability and maintenance are major concerns.

c) Waste-Heat Recovery from Diesel Generation unit

This system employs a water-jacket heat exchanger and an exhaust-heat boiler to raise process steam using the rejected heat of the diesel engine. Like the gas-turbine system, the system achieves a high generation per unit of thermal energy delivered to the process. The major drawback of diesel is the same as that of the turbine: at present, industrial diesels burn only natural gas or distillate. However, the adaptation of heavy-duty

residual-oil-burning marine diesel engines to industrial co-generation appears promising.

The high capital commitment required for co-generation demands careful consideration. The following should be considered when selecting purchase of power from a utility or generating it internally:

- Cost of purchased electricity versus cost of prime mover fuel including receiving and storing facilities
- Current and future availability of prime mover fuel
- Need for a standby power supply, which is essential
- Requirement to match process heat with electric generation in time and magnitude
- Requirement for continuous use of both process heat and electricity.
- Fairly high energy requirement of 5 MW or more
- Analysis of government benefits and statutory requirement
- Benefit of selling surplus electricity or steam to the utility or to others

8.5 Grid connected Operation

Captive power generation can be operated in parallel mode with the grid supply system. This method requires suitably designed voltage regulators for the captive generating equipment and governing system for the prime mover. The protection system has to be designed considering the system fault levels, possible interruption, operation of the generator in "Island Mode" etc.,

a) Synchronisation of Captive Generation unit with the Grid Supply

For operating Captive power generation unit in parallel mode with the grid supply system or 'synchronising', the following conditions are to be fulfilled:

1. Voltage of incoming machine is to be same as Grid bus voltage;
2. Frequency of incoming generator is to be same as grid bus frequency;
3. Phase sequence of incoming generator and grid system to be same.

The above conditions are achieved through a synchronising panel.

b) Islanding Operation

Most of the integrated continuous plants where the total Energy concept is adopted, the captive generation units are designed such that in the event of grid supply failure or grid system abnormalities the essential load or the entire plant load is catered by the captive generating unit. This method of operation is termed as 'Islanding operation'. Fast action di/dt relay (Rate of sudden increase in load current) and df/dt relay (Rate of sudden alteration in frequency) are used in the system relay co-ordination to facilitate smooth changeover to islanding operation.

A complete proper overall protective relay co-ordination, monitoring for efficient operation with the grid supply system scheme has to be ensured. Adoption to captive power generation shall assist in continuous and reliable source of uninterruptible energy for smooth plant operations.

Section 9 : Economic and Financial Evaluation Analysis

Most clients expect Energy Services Company (ESCO) to present some form of economic or financial analysis. It is also to the ESCO's own advantage to be proficient in simple cost/benefit analysis as well as risk assessments to ensure proper client selection.

Prior to an energy audit or data collection in a firm, the important questions are:

- Is there a reasonable potential to reduce energy costs?
- Is it an economic measure?
- Are energy cost reductions verifiable?
- Is the client firm a low risk for the ESCO?

While economic analysis is mostly used to compare alternative options and cost/benefits in a more global perspective, financial analysis is more suitable to explain to the client the firm's cost/benefit. Nevertheless, both approaches have their merit.

9.1 Economic Analysis

Four widely used methods of economic analysis are presented. It will be shown that they differ little from each other.

a) Levelized Costs of Energy Saved (CES)

$$CES = \frac{I \times d}{S \times \left(1 - \frac{1}{(1+d)^T}\right)}$$

where T = technical life of hardware.
S = annual energy saved in some convenient unit such as tons of oil, litres of LPG, kWh of electricity or m^3 of gas.
I = initial single investment.
d= discount rate as fraction, i.e. 10% means 0.1.

Note that this case is very special in the sense, that one single investment is allowed and no future additional operation and maintenance costs (O+M).

As an example consider deployment of higher efficacy lamps (C.F.L etc.) in place of conventional lamps (incandescent), with no additional future O+M costs.

Other ESCO proposals may require future additional investment or additional O+M costs. A typical example is use of automatic power fuse controller for control of demand and power factor, which requires future O+M costs as well as periodic replacement of the fuse elements.

In this case: (Version 2)

$$\mathrm{CES} = \frac{\left(\sum_{t=0}^{T} \frac{C_t}{(1+d)^t}\right) \times d}{S \times \left(1 - \frac{1}{(1+d)^T}\right)}$$

Where C_t=Annual costs. If $C_0 = I$ and $C_t = 0$ for all other t, we have the previous version. CES indicates to what extent it is less expensive to save one kWh of electricity than to spend it by doing nothing.

b) The Net Present Value (NPV)

The net present value (NPV) is defined as I $\sum_{t=0}^{T} \frac{R_t - C_t}{(1+d)^t}$

Where R_t = revenues associated with the proposal in the year t.
C_t = Costs associated with the proposal in the year t
d = discount rate, as fraction
T = technical life of the project, in years.

Annual revenues R_t of the project are mostly the annual energy cost reduction from implementation of the ESCO proposal. C_t are the additional investment, repair and replacement costs for the project.

Because this is not a financial analysis, costs C_t do not include repayment of loan principle and interest charges. In almost all cases R_0-C_0+=-C_0.

In other words at the end of the year 0, a single investment C_0 is placed, and revenues from the investment start already in the first year. The NPV

represents the "accumulated wealth" of the client firm from implementing and operating the project over its technical life T. An obvious conclusion is:

"Reject the proposal whenever NPV is smaller than 0."

c) **Long Range Marginal Costs (LRMC)**

The LRMC, also called "average future economic costs" are defined as:

$$\mathrm{LRMC} = \frac{\sum_{t=0}^{T} \frac{C_t}{(1+d)^t}}{\sum_{t=0}^{T} \frac{S_t}{(1+d)^t}}$$

Where,
C_t = costs associated with the proposal in the year t, in currency units
S_t = energy savings associated with the proposal in the year t, in energy units
d = discount rate as fraction
T = technical life on the project, in years

The levelized cost of energy saved, (CES), are just a special case of LRMC in the sense that the annual energy saved is constant. LRMC is a more general formula to accommodate fluctuations in annual energy savings.

LRMC represents the ratio of the present value of the costs over the present value of the energy saved.

d) **Cost annuity Per Unit Energy Saved (CA)**

The cost annuity (CA) is defined as:

$$\mathrm{CA} = \left(\sum_{t=0}^{T} \frac{C_t}{(1+d)^t} \right) \times \frac{\mathrm{CRF}}{\mathrm{S}}$$

Where CR $\frac{q^T(q-1)}{q^T-1}$ and $q = 1 + d$

CRF a function of d and T is called the capital recovery factor. It can be shown that CA is equivalent to CES.

e) **Decision Criteria**

The four economical indicators

- Levelized Costs of Energy Saved (CES)
- Net Present Value (NPV)
- Long Range Marginal Costs (LRMC)
- Cost Annuity (CA)

are more or less similar. The most general formula applicable to all cases is LRMC.

In practice, the CA and CES is widely used. Although the equations are formulated with respect to "energy saved, S_t, in the year t", they can be applied to any investment.

In the case of retrofitting a transformer with an on-load tap changes the question is how much does the saved energy S_t cost. However, if it is decided to replace the entire transformer and buy a new one with a much higher efficiency, the equation represents the future economic costs of energy distribution. In the latter case, St represents the annual unit of electricity distribution.

An ESCO proposal must be rejected if:

- NPV < 0
- LRMC, CES, CA are larger than the present electricity costs

In the first case, the investment would not increase the "accumulated wealth" of the client company. In the latter case, it is more beneficial for the company to waste energy than save it.

It is always technically feasible to save energy, however it is not always economical to do so.

f) Other Economical Indicators

The Internal Rate of Return (IRR) is defined as the discount rate at which NPV = 0. In other words it is necessary to find a number, called IRR, such that:

$$0 = \sum_{t=0}^{T} \frac{R_t - C_t}{(1+IRR)^t} = NPV$$

ESCO's may use the IRR in a discussion with clients on the cost/benefits of a proposal. However, very careful language is required to avoid eventual misunderstandings.

Well managed larger companies are split up in divisions, which propose projects for the next year's budget. Such proposals are then rated according to their IRR. This indicator is widely used, because company's interpretation of the IRR is the interest earned on their investment. In reality, the IRR is the interest earned on the outstanding balance of the firm's equity in the project.

Another point of confusion is the difference among economic and financial analysis. Companies calculate mostly on financial basis. The IRR also does not always exist or may become infinite. One should therefore use the IRR with caution.

The Dynamic payback period (DPP) is an indicator which companies use as criteria for investment the shorter the payback period, the better. DPP is defined as the year T where,

$$\sum_{t=0}^{T} \frac{R_t - C_t}{(1+d)^t} \rangle 0$$

In other words, beginning with the year 0 (zero) of the first cash flow, the discounted values of the annual net cash flow are summed until the total reaches a value of zero or greater.

Note that DPP is increasing with increasing discount rate if the net cash flow stays positive. This means, the higher the expectations of a company with respect to the interest earned on the outstanding balance of the firms equity, the longer the payback period.

g) Special Considerations

Modem computer spreadsheets feature built-in functions for NPV and IRR. However, the definition for NPV differ.

Some define N $\sum_{t=1}^{T} \frac{C_t - R_t}{(1+d)^t}$

The counting of the years starts at beginning of the year one.

Others use NP $\sum_{t=0}^{T} \frac{C_t - R_t}{(1+d)^t}$

The counting of the years starts at the end of year 0.

Frequently, an option is given to declare cash flows either at the beginning or end of the year. It is wise to test the NPV calculations by hand to find out which calculation method is used.

The built-in functions for IRR require the user to give an initial estimate of the IRR. It is best to first calculate NPV based on a user given discount rate d and select next an initial guess for IRR as follows:

If NPV > 0 set IRR = d
If NPV < 0 set IRR = d/2

h) The discount Rate (d)

The discount rated is widely viewed as the opportunity costs of capital. Before guessing d, one may consider to make an estimate:

D= Annual average inflation - annual interest rate

If the annual average inflation rate of a country equals 6% and banks would grant the company a loan for 14%, then d=14-6=8%.

Others define $$d = \left(\frac{\text{Annual average inflation rate}}{\text{Annual interest rate for bank loans}} X100 \right) - 100$$

With the above parameters, $$d = \frac{1.14}{1.06} X100 - 100 = 7.5\%$$

There is no sound theoretical basis to prefer one definition over the other.

i) Financial versus Economic Analysis

It is recalled that economic analysis requires only to estimate the discount rate d and fix the planning horizon or technical life T of the project. No other external parameters such as bank interest rate or inflation on O+M costs are considered. In addition, costs should be exclusive of taxes and duties, because the latter goes from one pocket to the other and do not deplete resources. A client firm may therefore question the numbers presented and argue about discrepancies.

In the day to day advisory work, it is more appropriate to use a net cash flow sheet and show the time series of cash flows. Basic features of a net cash flow sheet are given in the next paragraph. Todays personal computers and standard spreadsheet software make it fairly easy to set up a template which can be used to present the results in a structured way.

9.2 Financial Analysis

NCFS stands for NET CASH FLOW SHEET. It is a method to account for all cash inflows and outflows of a project implemented by a Firm. A firm may be any entity from the private and public sector.

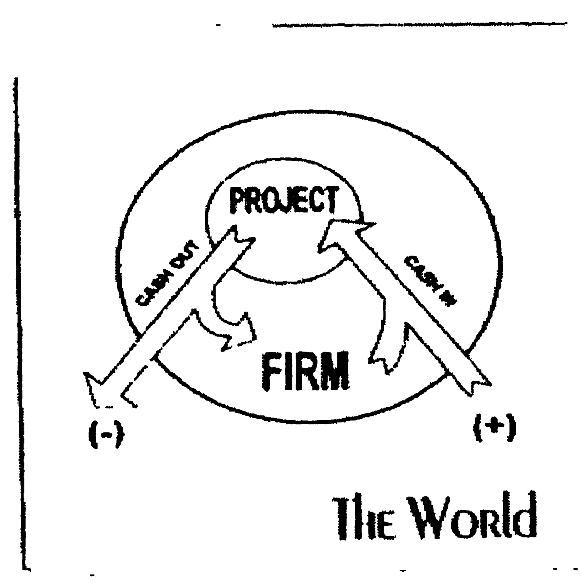


Figure 9.1: Annual Cash Flow to the Project

The project is implemented by the firm and therefore part of the firm's activities. For this reason it is drawn inside the firm. Annual cash inflows to the project are either from the firm or from the "World". The "World" represents all other firms the project deals with, mainly banks which given loan to the project, suppliers of equipment and consumables, and buyers of the goods or services the project generates.

a) NCFS Features

The NCFS is the ultimate way to show an explain all important economical and financial indicators of an investment in a project. The compilation of the net cash flow sheet allows the calculation of:

- The net present value NPV, before and after tax
- The financial rate of return, FIRR, before and after tax
- The static and dynamic payback periods
- The time values of future cash flows

The NCFS also gives a quick overview about cash flows of the proposed project, which will materialise in future years of operation. Even more, it does not treat NPV and IRR as single economical indicators of the project but rather displays them as time series. Users can easily assess the risks they expose themselves to by operating a project for too short or too long a period of time.

b) NCFS Components

NCFS is a set of number columns which represent specific cash inflows (+) or cash outflows (-) from the project over the planning horizon or the technical life of the project.

Additional number of columns is added to accumulate and analyse the cash flows.

Cash inflows (+) are:

- Revenues from operation of the project
- Equity from the firm
- Loans from the outside "world" (usually from a bank)
- Corporate tax savings on book depreciation of project
- Corporate tax savings on interest paid on loans

The later two are avoided costs of the firm through the project and therefore cash inflows to the project.

Cash outflows(-) are:

- Costs from operation of the project
- Investment in the project
- Interest paid on loans
- Repayment of the loan principle

The Net cash Flow is the sum of negative cash outflows and positive cash inflows.

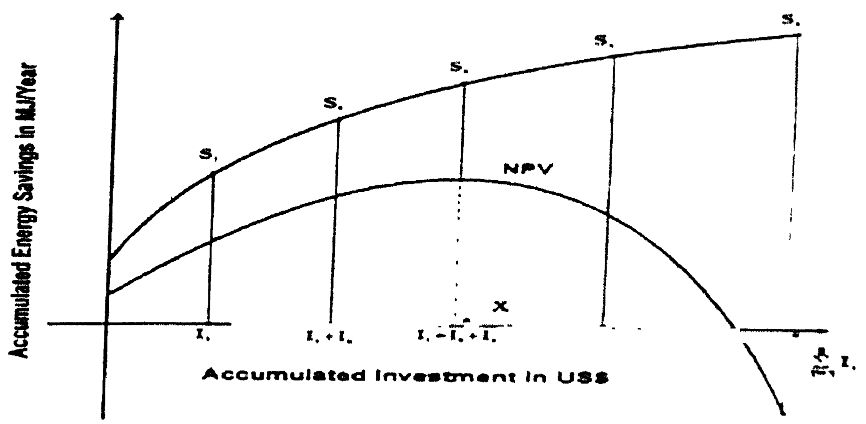
Additional non-cash flows:

- Annual book depreciation of the depreciable part of the investment
- The accumulated net cash flow
- The discounted net cash flow
- The accumulated discounted net cash flow, called the time series of net present values (NPV)
- The time series of FIRR

c) **Energy savings Versus Cost Effectiveness**

Saving energy is always technically possible. To what extent it improves the firm's economic viability is a different story. An ESCO should view or a process as a system where numerous options exist to save energy such as S_1, S_2, S_3, S_4, S_5. The corresponding investments are I_1, I_2, I_3, I_4, I_5. The anticipated amount of energy saved will approach asymptotically the best case scenario representing the present state-of-the-art.

The typical relationship between level of investment versus level of achievable savings including the NPV for a given level of investment is shown in Figure. 2. It is not advisable to go beyond investment level X, because of diminished benefits for the firm.



Source United States Environmental Protection Agency, Green Lights Program, Lighting Upgrade Manual, April 1994 (Modified version by A. KAUPP)

Figure 9.2 : Typical Relationship between level of Investment Versus Level of Achievable Savings

Section 10: Checklist For Electrical System

a) Sub stations and Transformers:

1. Locate the substation nearer to the load centre to minimise energy losses and improve tail end voltages.

2. Select and use low loss transformers.

3. Provide all necessary instruments for monitoring the performance of individual transformers.

4. Provide a separate lighting transformer for better control.

5. Select Power transformers with OLTC and auto control.

6. Identify under loaded transformers and redistribute the load to achieve optimum loading conditions.

7. Operate identical transformers in parallel, whenever required.

8. Switch off idle transformers, in cyclic rotation, on the primary side. If required, self heating tapes may be used to maintain the oil temperature within reasonable limits.

9. Switch off transformers and re-adjust the load on holidays and during power cuts.

10. Provide necessary circuit breakers and dis-connectors to transformers and adopt split bus system in sub stations to allow flexibility of operation.

11. Monitor the tap positions of distribution transformers on a seasonal monthly basis and re-adjust the same as and when required.

12. The bus bar sections parallel paths in the sub stations should be loaded equitably.

b) Load Management and Power Factor Improvement

1. Incorporate a warning system in the maximum demand indicator so as to enable immediate steps to be taken.

2. Transfer the operation of high unit loads judiciously to lightly loaded shift hours to reduce the maximum demand.

3. Flatten the load curve and maintain a high load factor.

4. Stagger starting and stopping of high HP Motors.

5. Stagger timings for working of machines and recess.

6. Avoid idle running of machines.

7. Operate the synchronous drives under unity PF condition.

8. Wherever storage facilities are available operate the Pumps during low load hours.

9. Provide programmable time based controls for exhaust fans to achieve cascade operation.

10. Install capacitors with phasetron control to modulate the requirement of reactive power.

11. Assess the average and peak load power factors and redesign the capacitor requirements.

12. Maintain the peak load power factor between 0.94 to 0.98.

13. Balance the capacitors as per the load.

14. Select capacitors with low dielectric losses such as polypropylene or any other mixed dielectric type.

15. Inform the Power House before switching on heavy loads.

c) Distribution System

1. Minimise LT distribution by increasing the HT distribution system.

2. It is preferable to provide ring main system for HT & LT distribution system to facilitate flexibility of operation and change over of loads. The Ring should be opened at the optimum point.

3. Provide as many parallel paths as possible. Depending on the loading conditions multiple runs of cables should be provided.

4. Draw fairly balanced multiple circuits from the secondary of the distribution transformers.

5. Check cable size and ensure that cables of requisite current carrying capacity are employed, taking into account the starting power requirements of machines.

6. Redistribute the loads to avoid circuitous feeding.

7. Ensure equitable distribution of loads on available parallel paths.

8. Install separate distribution and switch boards for power and lights for individual departments.

9. Replace old paper cables having a high leakage factor with new PVC / XLPE Cables.

10. Balance the loads on all the three phases within + 1% as Voltage imbalance results in higher losses.

11. Install capacitors near the load points or at the sub distribution board.

Case Studies

Case Study - 1

Availing Incoming BEST Supply at High Tension as Integrated Power Supply to Centralised Office Buildings

Background

This Company having a multi engineering business has a centralised office complex located in western part of India. A comprehensive audit was carried out for the above complex in 1998-99. Annually about Rs 62.3 lakh is being paid towards electrical energy charges. The complex has five blocks 'A','B','C', 'AEF' and 'Z' respectively.

Presently the supply from BEST is on L.T. basis with metering at various points of use of energy. While "Z" block is nearing completion, the renovation of block 'A' is ON. The category of consumer and tariff's applicable for various blocks when completed with appropriate load kW, kWh, RkVAh would be as follows:

Building Block	Category of consumer	Anticipated Annual Energy consumption		Peak load kW	Unit Rates		Anticipated Annual bill (Rs.lakh)
		KWhr Lakh	RkVAh Lakh		kWh, Rs.	RKVAh, Rs.	
"B"	C2	4.4	0.67	200	4.75 + FEC	2.40	24.4
"C" godown	GP2	3.51	0.48	125	4.00 + FEC	2.00	16.5
"C" lighting							
Meter-1	03/21	0.31	-	75	5.37 + FEC	-	1.80
Meter-2	05/024	1.18	-		5.10 + FEC	-	6.52
Meter-3	03/024	0.40	-		6.0 + FEC	-	2.57
AEF godown	GP2	2.86	0.55	70	4.00 + FEC	2.00	10.5
"Z" building (nearing completion)	C2	1.38	0.40	60 (Est)	4.75 + FEC	2.40	8.1
"A" (Future)	C2	8.8	1.20	400 (Est)	4.75 + FEC	2.40	47.67
Anticipated total		**22.84**	**3.3**	**930**	-	-	**118.06**

Note: Fire fighting and co-op society meters which consume very less energy are not listed.

FEC: Fuel Escalation charges; Est: Estimated load figures.

The tariff under HT category is much attractive compared to commercial/LT rates presently made applicable. Hence it is suggested to opt for a H.T. industrial category after installing independent transformer and connected switchgear for entire complex. It is gathered that for availing industrial H.T. connection, the

Case Study - 1 contd...

minimum commitment of annual energy should be 5.0 lakh units and 200 kVA demand for five years period according to BEST.

Present H.T. industrial tariff considered for techno-economics are:

M.D.Charges	: Rs.170/kVA (for 1000 kVA billing demand)
Energy charges	: Rs.1.97 + FEC per kWh (For 22.84 lakh units annually)
	+ Rs.1.0 per RkVAh (For 3.3 lakh units annually)

Anticipated savings due to change of category even with 1000 kVA as monthly billing demand would be Rs.40 lakh with an initial investment of Rs.30 lakh for arranging a suitable capacity transformer of say 1500 kVA with controls and switchgear and cabling arrangement including modernising of "AEF and "C" godown panels.

Even if loads of "A" block is not availed immediately, the maximum kVA requirement would be 600 kVA (with 0.8 p.f.) in which case annual H.T. category billing will work out as follows:

Billing demand	:	600 kVA	
Annual energy consumption	:	14.04 lakh units (including losses of transformers)	
Annual RkVAh consumption	:	2.1 lakh units	
Monthly M.D. charges	:	Rs.170 x 600	= Rs.1.02 lakh
Annual M.D. charges	:		= Rs.12.24 lakh
Annual energy charges	:	Rs.2.4 x 14.04	= Rs.33.69 lakh
Annual RkVAh charges	:	Rs.1 x 2.1	= Rs.2.10 lakh
Total			= Rs. 48.03 lakh

The present L.T tariff annual billing .... = Rs.70.39 lakh
(Including "Z" block)

Immediate annual savings possible (without any investment)= **Rs.22.36 lakh**

Case Study - 2

Shifting of Pump House Transformer (TR-3) to Intake Pump House

Background

This industry is one of the leading manufacturers of pulp and paper in Nepal. A comprehensive energy audit was carried out during the year 1997-98. The plant has a production of 9908.13 MT and had consumed about 190.2 lakh kWh of electrical energy during that year. Brief details about the plant transformer loading is given below:

Description	Volt	Amp	p.f.	kW	kVA	kVAr	Hz
Incomer of Intake pump house	351	103	6.0	62.7	62.7	0.00	49.8
Anticipated peak value of load	380	210	0.99	125	125	-	-

System Description

The incoming panel of intake pump house panel is receiving supply from pump house M.C.C. panel which is fed either by TG/DG or NEA(Nepal Electricity Authority). The size of feeder is 95 sq mm copper. While using any of this supply, the cable was getting heated up and the voltage drop was substantial (more than 7.5% of sending end voltage rated at 380 volts). Normally one pump (55 kW) operates round the clock and one more pump is running around 8-10 hours/day. Hence maximum load anticipated is 110 kW at 380 V. During survey, one no. of 300 kVA transformer was observed to be available as spare.

Proposal

Use the 11 kV/433 Volt, 300 kVA transformer released earlier, at location near intake pump house on double pole structure.

For this purpose 11 kV overhead (O/H) line "Dog" conductor along with accessories (spare available in township) has to be erected. And the present L.T. feeder can be left disconnected only to be used in case of any emergency. Hence the cable overheating can be avoided, better voltage level can be availed at receiving end and saving in distribution losses can be achieved.

Annual savings in Distribution losses	= 56,377 kWh
Value of energy savings	= NRs.2.48 lakh (Nepal currency)
Cost of implementation	= NRs.0.50 lakh (Nepal currency)
Simple payback period	= 0.2 years

Case Study - 3

Energy Monitoring

Background

This industry is an IT industry located in southern part of India. In an effort to improve the overall performance,the industry was exploring for energy saving opportunities in utility areas. The company was operating round the clock, with an annual energy expenditure of Rs 160 lakhs.

System Description

The company has strategically located buildings at various parts of the city. The building under consideration was fully air conditioned, in 3 floors on an area of 10000 sq. ft. The major utility areas were air conditioning, lighting and the computer systems. The annual energy consumption was 12 lakh kWh. The typical load measured during the daytime was 500 kVA of which only about 150 kVA was supplied from the state electricity board (EB); the rest was fed by captive generation. The power factor was quite low, around 0.65 to 0.75 (lag).

Observations

From the study of logbooks and previous EB electricity bills, the following points were observed.

- The transformer at the EB incomer was 750 kVA, but only about 150 kVA was drawn, as the contract demand with EB placed restrictions.
- The company paid a penalty of 15 - 20 paise per kWh due to the low power factor.
- There were no meters to monitor/control the demand and power factor within the building. As a result, the existing p.f. improvement capacitors were not used properly.

Recommendations

The company was recommended to install energy monitor/ demand controllers at the panels supplying the major energy consuming loads. These meters are capable of monitoring all the power parameters (Average voltage, current, frequency, power factor, kVA, kW, kVAr, kVAh, kWh, kVArh) apart from the demand control as customised by the user.

Benefits

The company was able to monitor and maintain the p.f. accurately at 0.95 or more by switching on/off of the capacitor banks. A savings of Rs.1.8 lakh annually was achieved. This measure also helped in avoiding the p.f penalty paid.

Result

The company has installed the energy monitor/demand controller at two strategic locations - investing Rs.1.5 Lakh resulting a payback period within one year.

Case Study - 4

Up-gradation and Relocation of Substation

Background

This industry is one of the leading zinc manufacturers located in south India. In the year 1992-93, the plant consumed 86 million units of electricity for the production of zinc, sulphuric acid and cadmium. A detailed energy audit was conducted in this plant in Feb-1993.

System Description

Main source of supply is the state Electricity Board. The supply is received at 110 kV substation. 11 kV cables are drawn to various 11 kV substations situated at load centres in the plant.

The 110 kV outdoor structure yard and the 2 x10 MVA power transformer are located at an elevated point. The switchgear and the control room is located at the lowest elevation. Hence it is learnt that during monsoon season the cable trenches get filled with water resulting in maintenance problem.

System Parameters

The incoming voltage level is not satisfactory. The lowest voltage recorded on the 110 kV side is 88 kV. The corresponding voltage on the 11 kV bus was 9.0 kV. The tap position of both the power transformers has been kept at no.5 i.e., the lowest tap available. This has resulted in the following losses.

- Reduction in the effective output of capacitor bank connected at the load points. Consequently there is no improvement in the power factor as expected and reduction in maximum demand. It is estimated that the capacitor unit output is only 60% of its rated capacity at present.
- Due to low bus voltage there is an increase in bus losses, cable losses and on the primary side of rectifier transformer.
- Failure of capacitors due to over voltages during off peak load hours and disturbances.

Transformer Load Management

The existing 2 x 10 MVA, 110/11 kV transformers are operated in parallel. At present the loading is about 71.63% peak wise. The optimum loading ratio works out to 0.3873. Hence under the present circumstance the loading has exceeded the optimum loading condition resulting in higher load losses. This

has resulted in high transformation losses and the all day efficiency of the transformers work out to 97.27%. Further the existing transformers are about 25 years old.

These old design transformers have higher losses.

Expansion Programme

It is planned to increase the production of zinc from 20,000 tons to 25,000 tons in 1st stage and up to 30,000 tons in 2nd stage. The 1st stage expansion results in 18 MVA of maximum demand and 21 MVA in 2nd stage expansion.

Proposals

Considering the expansion plans, the 1st stage expansion would result in loading the existing transformer to 90% and over after 2nd stage. Expansion, the loading of existing transformers would be to an extent of 5%.

Under the circumstance the proposal of increasing the capacity of transformer 2 x 20 MVA is considered. The percent loading after 1st stage expansion would be 45% and the after 2nd stage expansion would be 52.5%. Loading condition is nearer optimum loading limits. The transformation losses would be optimum. Also this would increase flexibility of operation i.e, even if one transformer fails the entire load can be taken on the other one. With this proposal it is estimated that the all day efficiency of the transformers would improve to 99.48%.

To further minimise the losses it is necessary to maintain the bus voltage at an optimum level. It is in this context that auto OLTC is recommended for the proposed 2x20 MVA transformer. With the setting and operation of the OLTC's it is recommended to maintain 11.5 kV always at the 11 kV bus. Consequently the tap positions of all the distribution transformer should bed changed to position no.1 (or 11,550 V primary).

In view of future loads, enhancing the capacity of transformers and consequent I crease in bus fault levels certain changes in the existing switchgear capacities are required like:

- Reconstruction of the 11 kV bus providing new SF6 breakers.
- Providing new 11 kV switch board (wherever required)

Also the possibility of avoiding the water logging in cable trenches during monsoon should be considered.

Under above circumstances, the constructing a new control room with new switch gear in the new location shown in the drawing i.e., at an elevated place near the transformer and outdoor yard location is happens to be the ideal load centre as it would be nearer to the cell house plant as well as new

melting plant. This would minimise the voltage drops and energy losses in the connecting cables.

Further the no. of days of plant shut down required and the consequent loss of production is reduced significantly.

It is estimated that the net cost of implementation would be Rs.250 lakh. Resale value of the existing 2 x 10 MVA power transformers and released switchgear units has been taken into consideration while arriving at the above estimation.

With this proposal the following benefits can be derived.

i. Reduction in Maximum Demand

The output of the capacitor units would improve and the rated reactive power out would be available for the system. It is estimated that an additional 2900 kVAr of reactive power would be available. This would result in the reduction of maximum demand by about 980 kVA. The savings in demand changes due to this reduction would be about Rs.8.2 lakh per year.

ii. Reduction in Rectifier Transformer Losses

The 2 nos. of rectifier transformers in cell house plant handle about 70% of the total energy consumed. Due to increase in bus voltage on the 11 kV side, the I^2R loss in the primary side of the transformers would get reduced to a considerable extent. It is estimated that there would be a savings to an extent of about 1.90 lakh kWh/year or Rs.1.90 lakh/year.

iii. Reduction in Distribution Transformer Losses

It is estimated that there would be a saving of about 63,500 kWh/year amounting to Rs.63,500/year in transformation losses of other distribution transformers due to improvement in bus voltage.

iv. Distribution Losses

It is observed that the sizes of the cables and the multiple runs used for different feeders are adequate. The bus bar and distribution losses have been estimated to be about 0.06%. Due to improvement in voltage, it is estimated that there would be a saving of about 45,600

kWh/year or Rs.45,600/year in cable and bus bar losses.

i. Control room at the new location (Proposed)

Total estimated cost of 2 x 20 MVA transformers with necessary switchgear, SF6 breakers, civil engg. works etc.	= Rs.300 lakh
Less Credits	
2 x 10 MVA 110/11 kV power transformers and switch gear released	= Rs.50 lakh
Net cost	Rs.250 lakh

ii. After II Stage of Expansion

a. At current electricity tariff

Savings in transformation losses	:Rs.34.29 lakh/year
Savings in MD charges	:Rs.8.20 lakh/year
Savings in distribution losses	:Rs.0.46 lakh/year
Total	Rs.42.95 lakh/year

b. Assuming an increase in electricity @ 33 1/3% over a period of 5 years : Rs.57.27 lakh/year

The simple payback periods under different conditions (worked out above) have been presented in the following table.

Simple payback periods in years

Sl. No.	Details	After I Stage Expansion		After II Stage Expansion	
		At current tariff rate	Assuming a hike of 33 1/3% in tariff	At current tariff rate	Assuming a hike of 33 1/3% in tariff
1.	Control room at existing location	5.3	3.9	4.2	3.1
2.	Control room at proposed new location	7.3	5.5	5.8	4.4

Recommendations

Based on the discussions made in section 1.2 above the following recommendations have been made:

i. To replace the existing 2 x 10 MVA 110/11 kV power transformers by 2 x 20 MVA 110/11 kV OLTC-auto power transformers.

ii. To construct a new control room at the proposed new location (which is the load centre also) with new switch gear and 11 kV bus and panels.

iii. To maintain a voltage of 11.5 kV on the 11 kV bus always by proper operation /setting on OLTC's of proposed transformers.

iv. To change the tap positions of all the distribution transformers to no.1 (i.e., 11,550 Volts primary).

The total savings in energy losses after II stage of expansion is estimated as:

Savings in power transformer losses	= 31.75 lakh kWh/year
Savings in rectifier transformer losses	= 1.90 lakh kWh/year
Savings in distribution transformer losses	= 0.64 lakh kWh/year
Savings in bus bars and cable distribution losses	= 0.46 lakh kWh/year
Maximum demand released	= 980 kVA
Total cost of savings in energy and maximum Demand	= Rs.42.95 lakh/year
Cost of implementation	= Rs 400 lakh
Simple Payback period	= 9.3 years

Case Study - 4 contd..

This measure has improved the plant specific energy consumption by 3% (high profit generation) and increase in production capacity (high profit generation not quantified). This has also resulted in continuous production and system reliability.

Case Study - 5

Deployment of Centralised (Electrical) Energy Monitoring System

Background

This industry is an integrated newsprint manufacturer located in south India. In the year 1997-98, the plant consumed about 1839 lakh units of electricity for the production of 85038 MT of newsprint. A detailed energy audit was conducted in this plant in Dec-1998.

Based on 98-99 data for 6 months, following are the maximum demand billing.

Month	MD (MVA)	Excess demand over minimum billing demand (MVA)	Excess demand over Contract Demand (MVA)	Remarks
April	33.92	11.42	3.92	150% penalty paid
May	22.28	-	-	MD charges @ Rs.132 per kVA paid
June	23.92	1.42	-	-do-
July	32.12	9.62	2.12	150% penalty paid
August	22.64	0.14	-	
September	22.64	0.14	-	
Total	22.74	6.04		

Excess demand charges (over contract demand) paid over 6 months	= Rs.11.95 lakh
Annual excess demand charges	= Rs.23.90 lakh
Total investment envisaged	= Rs.30.00 lakh
Simple payback period	= 1.25 years

Note1 : The notional benefit for system improvement, energy monitoring and bench marking is not taken into account.

Note2: The plant can even maximise the benefit by controlling the demand below minimum billing demand.

The details of the system to be adopted is given below:

1.0 ENERCON Centralized (Electrical) Energy Monitoring System

The system comprises of a PC based Energy Monitoring System (eLAN) networked to multifunction meters (Trivector Monitors and Power and Energy Monitors).

The networked Energy Monitoring System proposed would enable the purchaser, M/s. Hindustan Newsprint Limited (HNL), to monitor the energy consumption of the entire plant as also various subsections of the plant in real time. Some of the major advantages of the proposed system are:

The instrumentation provided at the EB incomers helps in monitoring and verifying the EB billing readings as also track the demand profile as seen on the EB lines and the TG incomers. This would enable the HNL to control the demand by suitable strategies.

The instrumentation provided at various load centres and major loads enables HNL to monitor the energy consumption at these points. The eLAN system also computes the energy balance at various nodes and computes the system losses to enable formulation and implementation of loss elimination/reduction schemes thereby effecting energy conservation. The eLAN system also computes the specific energy consumption of the plant and the sub processes. This would enable HNL identify the process inefficiencies and improve the same leading to energy conservation.

The multifunction instrumentation and eLAN system enables HNL to monitor the electrical system and major equipment healthiness. The run-hour log for major equipment is maintained by the system. This would help in better and cost effective maintenance compared to the open loop time based systems thereby improving the equipment availability and overall UP time of the plant.

The highlights of the eLAN system are as under:

1.1 Energy Management System eLAN

The eLAN software runs as an application under MS windows and can network several monitors.

The eLAN software enables collection of data, viewing of data in graphical and tabular formats and processing of data as desired using standard, widely used packages such as MS Excel, etc. The software generates on-line reports on measured as well as calculated parameters.

1.1.1 Alarms

The Alarm and System message records and archives events such as Alarms, Faults and operating status. This information can be visualized

chronologically on message displays or printed out as message logs. Different alarm messages are possible for set points for different signals. The message is composed of Signal names,

Message Date and Time of occurrence, etc.

1.1.2 Mimics

During configuration, dynamic points can be assigned and stored with user defined functions. The process values can be displayed alpha-numerically as well as in the form of Dial gauges, Trend windows, Bar graphs, etc. Attribute changes such as colour changes, blinking, etc., can be incorporated.

1.1.3 Trends

The Trend screens display electrical parameters in a graphical form. Trend pages can be selected with upto four trend curves for desired parameters on each page as per the requirements of the application.

1.1.4 History

The past data also can be displayed in a graphical form where the time period of the graph and parameter selection for the display is user determined.

1.1.5 Reports

Reports show data on an hourly, shift-wise, daily, monthly basis, etc. The same can be enabled for logging also.

1.2 Communication Network

The energy monitoring system utilises an Rs 485 network as the backbone network. The PC is connected to the RS 485 network through ENERCON 's Data Converter (converts RS 485 to Rs 232). The multifunction meters are connected to the Rs 484 network in multi-drop mode through connector kits. The communication network diagram is attached to the proposal.

1.3 Instrumentation

The instrumentation proposed comprises of 3 nos. of Enercon make Trivector Monitors (2 already in use at the plant), type EM 3480 with import/export option and RS 485 communication port, 64 nos. ENERCON make Power and Energy Monitors, type EM 3360 with RS 485 communication port. The instrumentation deployment is attached to the proposal.

Case Study - 6

Energy Savings by Deployment of Lighting Transformer

Background

This industry is engaged in large fabrication works for power sector, petrochemical and fertiliser plants located in western India. In 1996-97, the plant consumed about 54 lakh units of electricity for the production of 8596 MT of fabrication. A detailed energy audit was conducted in this plant in the year 1997.

System Description

The total connected lighting load was 430 kW (approx)

Total lighting load measured are:

a.	MLDB - I	=	47.48 kW
b.	MLDB - II	=	42.70 kW
c.	MLDB - III	=	94.20 kW
d.	MLDB - IV	=	46.67 kW
			231.05 kW

The present voltage level measured was found to be 230 Volts and above at various supplying points.

Proposal

If voltage level is reduced by 8 to 10% (i.e., 210-220 volts) then 10-15% energy savings can be achieved. Hence the plant was advised to deploy presently available 500 kVA transformer (located in MLDB - III and MLDB - IV) exclusively as lighting transformer thereby reducing investment.

Additional benefit	=	Longer life of luminaires,
	=	Lesser replacement cost
Energy savings per annum (taking 10% savings)	=	23.10 x 12 x 300 kWh
	=	83,160 units
Value of energy savings per annum @ Rs.4.33 per unit	=	Rs.3.60 lakh

To implement above, the plant can procure voltage controller of suitable rating 100 kVA each for above locations.

Cost of implementation = Nil (Due to available extra transformer)

Simple payback period = Immediate

Case Study - 7

Cyclic Operation of Transformers

Background

To increase their competitive advantage over new entrants in the market, a leading two wheeler manufacturer in western India was looking for options to control its energy costs. With an annual (92-93) energy bill of Rs.1090 Lakhs (only electrical energy), the option was to look mainly at electrical areas for opportunities to conserve energy.

Existing system review and observation

The plant had total 8 substations at various load centres to cater to the load with the help of 28 nos. 11kV/433 Volts, 2000 kVA distribution transformers. The annual load factor was calculated from logbook data to be 44.33% (loss load factor 0.37) whereas the daily load curve was monitored and the load factor was calculated to be 49.75%. The loading pattern of the transformers was analysed, and in most of the cases, they were found to be satisfactory. However a few observations were made:

- Substation 1: one transformer kept as hot standby though cyclic operation is followed to avoid moisture ingress.
- Substation 3: Transformer B is under-loaded (24.4%) and can be transferred to 'A'&'C' while cyclic operation can be scheduled.
- Substation 7: Transformer B is under-loaded (9.4%) and can be transferred to 'C' while cyclic operation can be scheduled.
- Substation 8: Only one Transformer B is loaded (58%) and one transformer kept as hot standby while cyclic operation can be scheduled.

The minimum and maximum temperature recorded are 120 ^{0}C - 420 ^{0}C.

Relative humidity varies from 60-90%.

Suggestions made for improvement

In a joint meeting with the plant it was decided to switch off the primary of transformer at substation number 1 & 8 to save no load losses. The plant was also advised to transfer the loads from one transformer to another in substations 3 & 7 to

avoid under-loading of transformers as well as save the no-load losses by scheduling the operation of them in a cyclic manner.

Results

The plant management immediately adopted this proposal in substations 1,7 & 8. At substation 3 it was taken up later to suit operational convenience.

The implementation of above proposals together saved 16,92,000 units annually generating a resource of Rs. 5.87 lakhs (at an unit price of Rs.3.47/-) for the plant .

Simple operating practice formulation and adherence to the same helped the plant to save substantial amount without any investment.

Caution

In substation 3 transferring the loads were not easy in the absence of bus-coupler arrangement. An increase in plant load factor may call for reverting back to the original load allocation plan for the transformers.

Conclusion

By simple operational management of transformer loads and scheduling, it is possible to save substantially, without being too apprehensive of transformer operation, which is a static device operating at high efficiency level.

Case Study - 8

Bus Voltage Co-ordination

Background

This industry is a jute mill plant producing jute sacking products and sale yarn located in southeast India. In the year 1997-98, the plant consumed about 124 lakh units of electricity for the production of 29704 MT of jute products. A detailed energy audit was conducted in this plant in Aug-1998.

System Description

Contract Demand: 2.125 MVA

Minimum billing Demand: 1.8 MVA @ 80% of C.D

Transformer Details:

Power Transformer - 1 x 3 MVA, 33 kV/11kV, manually operated, OLTC provided

Distribution transformers

5 nos. of 11 kV/433 V transformers (0.6 MVA, 0.75 MVA, 1.0 MVA, 1.5 MVA, and 1.7 MVA) with off load tap changing facility

Distribution system

The power transformer OLTC is manually operated when voltage observed during their hourly round. The variation in bus voltage is 29-35

Observations

Present System values observed:

Load factor:	0.91
kVAr:	793
Voltage:	11.0 kV

By reducing the voltage to 10.6 kV, the kVAr drawn was reduced to 615 and power factor improved to 0.94

Proposal

To maintain the 11 kV bus at 10.6 kV and to adjust the distribution transformer tappings automatic control of OLTC to be provided at power transformer was proposed.

Results of computation

- Improvement in power factor
- Reduction in demand and reactive power

Estimated saving in energy saving	= Rs.6.29 lakh/annum
Cost of investment	= Rs.1.0 lakh
Simple payback period	= 2 months

Case Study - 9

Release of Transformation Capacity by Load Management

Background

This industry is a fertiliser plant located in West India producing concentrated Nitric acid and Nitro-Phosphate. A detailed energy audit was conducted during 1996-97.

System Description

The Concentrated Nitric acid and Nitro Phosphate section has three transformers of 1750 kVA. The loading of the transformers is 40.91% and 56.9% and one of them is a hot standby. The present kVA load on these transformers is high in comparison to the active loading on account of low power factor (0.7). The table below summarises the loading on the transformer.

Transformer Nos.	Rated kVA	Measured		% loading
		kVA	Pf	
Trf-1	1750	715	0.7	40.9
Trf-2	1750	Standby	-	-
Trf-3	1750	995.75	0.65	56.9

Proposal:

It is proposed to improve the power factor of the distribution network and reduce the kVA loading of the transformers and release the standby transformer.

The table below summarises the proposed loading on the transformers.

Transformer Nos.	Rated kVA	Actual load in kVA @ 0.9 Pf	% Load
Trf-1	1750	556.7	31.8
Trf-2	1750	-	-
Trf-3	1750	719	41

The revised loading on the transformers at an improved power factor is 31.8% and 41.0%. From the above, it is seen that the transformers are optimally loaded and necessity of a standby transformer does not exist since pf improvement yields reduced kVA loading of transformers. Hence, the hot standby transformer could be released.

Releasing 1 x 1750 kVA transformer (standby) after improving pf of loads results in:

Energy savings	= 18396 kWh/annum
Cost savings without any investment	= Rs.45070/annum

Case Study - 10

Power Factor Management on LT Side

Background

This industry is one of the largest pharmaceutical company located in south india. The plant produces bulk drugsand formulations.The plant consumed about Rs.63 lakhs value of electrical energy during the year 1995-96. Comprehensive energy audit was carried out in 1996 in an effort to improve the overall system performance and achieve cost reduction through better electrical system efficiency.

System Description

The plant is comparatively wide spread with a number of long length power cables, accounting for high distribution losses. Though the monthly average power factor was around 0.9, the instantaneous power factor at some of the MCC panels was observed to be as low as 0.6 to 0.7, leading to a close analysis of LT cable losses in such a large system.

Suggestions for improvement

At most of the MCCs the load was also fairly constant. A simple solution suggested was suitable fixed type capacitors to improve the power factor at the loads / panels to near 0.9. The most possible choice was to have capacitors at MCCs.

Achievements

With the simple measure of improving power factor at MCC panels, the savings in power consumption was observed to be 10.92 kW. As the plant was in operation for 8000 hours the annual energy savings were 57002 units (or Rs.2,54,228/-). The investment for implementing the measures was Rs.32500/-.

Results

The above study demonstrates the benefit of improving the power factor downstream in a large industrial distribution network resulting in substantial saving in distribution losses. The additional benefits due to the implementation of the measures are

- Reduced heating in cable terminals
- Improvement in system power factor

Case Study - 11

Power Quality Improvement

Background

The plant is one of the largest battery manufacturing unit in Western India producing industrial, automotive and tubular batteries. Plant has state of art machinery, producing more than 100,000 batteries per month. Power quality and Harmonic audit was carried out in this plant.

System Description

The plant has an electrical distribution network, comprising of one 11 kV/415 V, 2000 kVA distribution transformer and 12 power control center to cater various loads such as rectifier, air conditioning, A.C Motor, compressor fan, pumps, computer controlled measuring instruments, etc. Normal problem experienced due to the poor power quality was transformer over heating, motor failure, fuse blowing, capacitor failure and malfunction of control due to extra circulating harmonic current.

The harmonic factor of the transformer was studied and analysed. It was found to be above the limits prescribed by IEEE 519. This was due to the plant using 10 rectifiers of 54kVA fed from one power control centre. Normally, about 8 to 9 rectifiers are in operation loaded to 75% of their capacity. Total harmonic distortion of 52% was observed, predominantly 5^{th}, 7^{th} and 11th harmonics. Most of the time the operating power factor is less than 0.6 and system configuration does not include any power factor correction capacitor or harmonic filter.

Based on the measurements taken at rectifier & power control center a suitable 125kVAr-tuned automatic harmonic filter was recommended to provide power factor correction at the fundamental frequency and maintaining the total harmonic distortion percentages well below the IEEE-519 guideline limits.

Measurement with 125 kVAr, tuned Automatic Harmonic filter

Parameter	**Unit**	**Without filter**	**With filter**
Active power	kW	210	205
Apparent power	kVA	350	223
Power factor	Lag	0.60	0.92
Voltage	volts	405	414
Current	Amps	499	311
Frequency	Hz	50	50
THD (I)	%	52	<15
THD (v)	%	>8	<5
5^{th} Harmonics current	%	44	<8
7^{th} Harmonic current	%	22	<7

Result:

125 kVAr tuned automatic filter provided resulted in bringing down total harmonic distortion of current and voltage as per IEEE 519 and also improved the system power factor to 0.92. Annual energy saving was realized as given below:

Annual Energy savings = 49,920 kWh (due to reduction in distribution loss)
Annual Energy savings = 38,400 kWh (due to harmonic loss reduction)
Total Annual Energy savings = 88,320 kWh
Release in Demand = 127 kVA
Annual Cost savings = Rs 2.2 lakh
Investment cost incurred = Rs 2.8 lakh (for the harmonic filter)
Simple Payback period = 1.3 year

Case Study - 12

Application of Passive filters

Background

This is an integrated newsprint manufacturing industry located in south India. In the year 1997-98, the plant consumed about 1839 lakh units of electricity for the production of 85038 MT of newsprint. A detailed harmonic audit was conducted in this plant in Sept-1999.

System Description

The plant operates at 3 different voltage levels 11,000 volt (primary Distribution), 3300 volts (Secondary distribution) and 415 Volts (L.T. Distribution). The plant is having a steam turbine driven generator of total 15MW capacity and one diesel generator of 2,500KVA capacity for emergency supply. L.T. Capacitor has been installed for controlling reactive power consumption at various load centers. Due to this the P.F. has improved to 0.9 and above at some of the load centers.

An analysis of the paper breaks over the past number of month shows that outage due to paper break is very high. Electrical and harmonic measurements were carried out in the paper machine section to identify THD and consequential losses.

The main aim of the study was Harmonic measurements at various points of common coupling and recommendations for corrections. The study analysis included taking the various electrical related measurements using the sophisticated data logger as per IEEE-519 and G-5/3 standards. RCC inter-logger (accuracy class of 0.5) was used to measure instantaneous, maximum, minimum and average values of kW, kVA, kVAr, PF, Hz, I, V respectively at transformer 17, 18, 19 & 20 and all non-linear load connected to these transformers.

The table-1 & 2 below represent the measured values of power and level of harmonic distortions present at different load points.

Case Study - 12 contd..

Table – 1: Data Of Power Measurements At Plant Machine Section

Load Name	KW		kVA.		PF		Voltage		Current		Frequency	
	Min.	Max.	Min.	Max.	Min.	Max	Min.	Max.	Min.	Max.	Min	Max.
Transformer-1	199	232	369	396	0.55	0.58	232	240	415	652	49.4	49.7
Transformer-2	726	770	1041	1061	0.69	0.72	225.4	229.1	1390	1714	49.4	49.5
Duo former forming roll motor	78.1	79.8	114	116	0.68	0.69	227	228	165	186	49 5	49 5
Duo former couch roll motor	76.2	77.2	111	113	0.68	0.69	227.3	228.8	164	175	49.4	49 5
Pickup suction roll motor + Suction roll motor	91.7	93.3	130.9	132.7	0.70	0 70	227.6	229.1	193.8	198.9	49.5	49 5
Stone roll motor	75.7	76.4	112.8	113.7	0.67	0.68	227	229	166	174	49 5	49 5
Top grooved roll	169. 8	171.4	266.5	269.2	0.63	0.64	225.8	229.8	372.8	4064	49 5	49.5
Bottom grooved roll	171. 1	177	272	281	0.62	0.63	227	230	322	543	49 5	49 5
Transformer-3	326	335	521	536	0.62	0.63	229	233	628	861	49.4	49 4
Dryer motor-1	37	38	66.7	67.5	0.55	0.56	230	233	95	98	49 4	49 5
Dryer motor-2	68.9	69.8	105.6	106.6	0.65	0.66	230.9	233.5	147	156	49 4	49 5
Dryer motor-3	67.3	68.3	18.18	109.6	0.62	0.63	230	233	151	159	49.43	49 5
Dryer motor-4	40.8	42	76	78	0.53	0.54	229	233	88	155	49 5	49 5
Reel motor	64	64	103	103	0.61	0.62	230	233	144	153	49 4	49 5
Calendar motor	36.9	50.8	59	81	0.61	0.62	231	233	81.9	123	49 4	49 5
Transformer-4	47	81	14	299	0.09	0.7	228	242	15	914	49 4	49 5

Table – 2: Data Of Harmonic Measurement At Plant Machine Section

Load name	THD(V)		THD(I)		3rd THD		5th THD		7th THD	
	Min.	Max.	Min.	Max.	I	V	I	V	I	V
Transformer-1	4	6.8	41.9	51.5	1.55	0.15	47.83	3 77	15 52	2.09
Transformer-2	7.4	10.1	28.7	31.7	0.28	0.25	29.19	8.54	1.60	0 51
Duo former forming roll motor	8.4	10.7	39.8	46.1	7.0	0 06	42.9	8.3	8 99	0 67
Duo former couch roll motor	8.4	10.9	41 6	46 2	3.77	0 41	40.98	8 62	9 96	0 78
Pickup suction roll motor + Suction roll motor	8.2	10.9	34 5	36 9	0.96	0 29	43 51	8 13	2 21	0 76
Stone roll motor	8.2	10 7	41.6	45.8	2.7	0 17	41.65	8 6	9 64	0 55
Top grooved roll	8.3	10.8	30 2	33	1.9	0 28	29 58	8 6	4 3	0 71
Bottom grooved roll	8.1	0.8	30.7	36 7	3 48	0 17	28 62	8 91	4 68	0 48
Transformer-3	7.4	8 3	46.5	51.5	0.76	0 08	47 95	7.04	15 82	2 86
Dryer motor-1	7.0	8 4	65 2	70.6	0.41	0 07	59 27	6 69	31 05	2 37
Dryer motor-2	7.4	8.2	53 4	56.1	0.56	0 04	5 13	7.05	19.26	2 31
Dryer motor-3	7 4	8.2	52	56	1.68	0 05	49.3	6 73	18 98	2 51
Dryer motor-4	7 4	8.2	78	81 5	0 32	0.04	65 57	7 17	39 9	2 22
Reel motor	7.5	8.3	51 2	55 4	5.24	0.30	4.18	6 8	1 39	2.71
Calendar motor	7 2	8.3	32.	37.4	1 65	0 05	33 72	7.33	3 02	2 25
Transformer-4	1.3	7.4	0	86.8	6.3	0 1	4 11	1 98	42.19	0 75
	1.9	4.5	0	62.8	0.99	0.02	53 76	2 64	2 08	0 2
	1.7	6.3	0	58	1.11	0 05	48 78	0 51	18.34	1.21

Transformer-1: (1.6MVA,11KV/415V)

Proposal

Based on the analysis an addition of capacitor in the range around 900 kVAr can magnify 5th harmonic while capacitance around 450 kVAr can magnify 7th harmonics. Capacitors do not create harmonics, but depending upon the amount of capacitance due to harmonics, there will be an increase in the magnitude of harmonics flowing within the circuit.

It is therefore recommended to connect 300 kVAr, 4.7th tuned, 6-stage automatic harmonic trap to control the flow of harmonic currents from this non-linear load to industrial power system.

This shunt filter is expected to maintain the power factor above 0.9 during most of the loading condition while reducing the harmonic level near to the limit prescribed by IEEE-519.

Transformer-2: (2.0MVA, 11KV/415V)

Proposal:

Based on the analysis that an addition of capacitance in the range around 1100 kVAr can magnify 5th harmonic while capacitance around 560 kVAr can magnify 7th harmonics.
It is hence, recommended to connect 700 kVAr, 4.7th tuned 7-stage automatic harmonic trap to control the flow of harmonic currents form non-linear load to system. This shunt filter is expected to maintain the power factor above 0.9 during most of the loading condition while controlling the harmonic level near to IEEE limits.

Transformer-3: (1.6MVA , 11KV/415V)

This transformer is feeding non-linear load like Dryer motor (4nos.), Paper roll motor, Calender motor and reel motor individually controlled by six-pulse converter fed D.C.Drive. It has been observed that the pf is varying between 0.62-0.72 with an average active power of 326-335KW . Total harmonic distortion of voltage is about 8.3% and current distortion is around 51.5% predominantly with 5th, 7th and 11th harmonic contributing 48%,16% and 7% respectively. Both current and voltage harmonics are found above the limits.

Case Study - 12 contd..

Proposal:

Based on the analysis further addition of capacitance in the range around 1100KVAr can magnify 5^{th} harmonic while capacitance around 560 kVAr can magnify 7^{th} harmonics. It is recommended to connect 400 kVAr,4.7^{th} tuned 8-stage automatic harmonic trap to control the flow of harmonic currents form this non-linear load to industrial power system.

Transformer-4: (1.6MVA , 11 kV/415V)

Proposal:

Based on the analysis, an addition of capacitance in the range around 900 kVAr can magnify 5^{th} harmonic while capacitance around 450 kVAr can magnify 7^{th} harmonics. It is thereby recommended to connect 3590 kVAr, 4.7^{th} tuned 7-stage artomatic harmonic trap to control the flow of harmonic currents form this nobn-linear load to industrial power system.This shunt filter is expected to maintain the power factor above 0.9 during most of the loading condition while controlling the harmonic level near to IEEE limit.

Definitions

Definitions, System Parameters Calculations and Formulae

1. Load Factor = $\dfrac{\text{Average Load over a designated Period}}{\text{Peak Load in that Period}}$

2. Plant Factor = $\dfrac{\text{Average load on the plant}}{\text{Rated capacity of the plant}}$

3. Capacity Factor = $\dfrac{\text{Average Load on the machine}}{\text{Rated capacity of the machine}}$

4. Diversity Factor:

   a) Substation level = $\dfrac{\text{Sum of the peak loads on feeders}}{\text{Peak load on the substation}}$

   b) Transformer level = $\dfrac{\text{Connected load on the Transformer}}{\text{Peak load on the transformer}}$

   c) Distribution System = $\dfrac{\text{Sum of Maximum Demand of individual loads}}{\text{Maximum Demand of the system}}$

5. Demand Factor : $\dfrac{\text{Maximum Demand of a system or part of a system}}{\text{Connected load of the system or part of the system}}$

6. Loss Load Factor

   L.L.F. = $\dfrac{\sum I_x^2}{I_{max}^2 \times 8760}$

   $\sum Ix^2$ = $I_1^2 + I_2^2 + \ldots + I_{8760}^2$

   I max = Peak load current (in an year)

7. Transformer Efficiency and Losses

   a. Efficiency = Output (Power) / Input (Power)

   b. All day efficiency = $\dfrac{\text{Energy output}}{\text{Energy output + Energy losses}}$ (in a day of 24h)

c. Total losses = Iron losses + Copper Loss (I^2 R Loss) kW

d. Annual Iron Losses= k x t kWh

Where k = Fixed loss in kW
t = time in hours of operation in an year

e. Copper loss = I x LLF x η_f x t kWh

Where
I = Full load copper loss in kW
LLF = Loss load factor
η_f = efficiency at full load
t = time in hours of operation

8. Energy Losses In Cables And Busbars

Savings in energy losses = I^2R x LLF x t kWh

Where
I_x = Load current (in A)
R = Total resistance
LLF = Loss load factor
t = Time in hours of operation